

Evaluating the potential long-term and cumulative impacts
from dredging to accommodate boat access in Green Bay
and Lake Michigan in Door County, Wisconsin.

Final Report

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Introduction

Recent low water trends on Lake Michigan and the Bay of Green Bay have caused the shoreline to recede from private and public piers and docks in many communities along the coastal areas of Door County, WI. As a result of these trends requests for permits for dredging for boat access to existing piers continue to increase. Some current dredged boat access channels extend out as much as 100 m from the Ordinary High Water Mark, and are often cut through bedrock. In addition, depending on the site location and water level regime, maintenance dredging is often required to keep these channels open. Intuitively, there are concerns about the short-term, long-term and cumulative impacts of creating and maintaining these boat access channels. There is little information in the scientific or management literature pertaining directly to this issue. Increased turbidity of the water immediately following dredging clearly has negative short-term impacts on benthic communities that may be covered by settling particles (e.g. Germano & Cary 2005). Attenuation of light is also a potential short-term problem for aquatic plants (Davis & Brinson 1980, Dennison et al. 1993, Wood & Armitage 1997, Best et al. 2001). In addition, it is clear that sediment can accumulate in dredged channels more than in adjacent areas, evidenced by the need to re-dredge channels periodically (Germano & Cary 2005). However, there are essentially no studies of the long-term impacts of dredging boat access channels on aquatic habitats or biological communities. Concerns have been expressed by staff of the Wisconsin Department of Natural Resources and others, particularly in regard to dredging for private boat access; e.g., are these disturbances exacerbating the establishment and spread of invasive species; are these changes negatively impacting other indigenous species.

Based on the lack of background information in the literature and the concerns over the potential longer-term impacts, it was determined that a study was needed to accurately determine and document the effects of dredging boat access channels on habitat quality and biological communities. The primary objective of the current study was to evaluate the cumulative impacts of these dredgings on sediment characteristics, aquatic plant communities, benthic macroinvertebrate communities, and the occurrence of aquatic invasive species at locations on the Green Bay and Lake Michigan shorelines of Door County, WI.

Methods

Study Design and Site Selection:

The study was designed to evaluate the potential long-term and cumulative impacts from dredging to accommodate boat access in Green Bay and Lake Michigan in Door County, WI. In order to accomplish this objective within a single season, as necessitated by the permitting issuance timeline, comparisons were made among sites with differing histories of dredging, exposure and substrate type on the Green Bay and Lake Michigan shorelines of Door County, WI. This approach uses a snapshot study of sites that were previously dredged as a surrogate for long-term monitoring studies of sites following dredging. In consultation with the WI DNR staff, 69 potential sites were identified with the following characteristics:

- Previously dredged sites (with various times since dredging last occurred)
- Natural sites adjacent to previously dredged sites and proposed dredge sites.
- Exposed sites (relatively unprotected from wave action)
- Protected sites (located in bays)
- Various predominant substrate types (bedrock, cobble, sand)

We selected 24 sites that represented all except one of the 12 possible combinations of the above three factors (dredge history, exposure, and substrate type; see Table 1 and Appendix Table A1). No sites were identified that were located in exposed areas with sand as the predominant substrate and which had been previously dredged. Each site was sampled twice between May and September 2008. Site selection also ensured that locations from both the Green Bay and Lake Michigan sides of Door County were included in the study.

Table 1. Experimental design grid showing sites without a pier selected for study in summer 2008 in Door County, WI. Note that no sites were available that were in an exposed location with a sand substrate and that had been previously dredged. Principal author of the study design was Steve Galarneau, WI DNR.

PROTECTED BAY	Bedrock	Cobble	Sand
Previously dredged	90. Moonlight Bay 23. Sawyer Harbor	84. North Bay 17. Little Sturgeon Bay	81. North Bay 72. Sand Bay
Undisturbed	92. Moonlight Bay 24. Sawyer Harbor	16. Little Sturgeon Bay 83. North Bay	101. Baileys Harbor 80. North Bay 33. Egg Harbor 71. Sand Bay

EXPOSED (OPEN COAST)	Bedrock	Cobble	Sand
Previously dredged	113. Whitefish Point 30. Egg Harbor	11. Little Sturgeon Bay 45. Ephraim	<i>None available</i>
Undisturbed	112. Whitefish Point 65. Sister Bay	12. Little Sturgeon Bay 44. Ephraim	120. Egg Harbor 111. Whitefish Bay

Table 2. Experimental design grid showing sites with a pier present selected for study in summer 2008 in Door County, WI. Note that no sites with a solid pier were available that were in an exposed location with a sand substrate and that had not been previously dredged. Principal author of the study design was Steve Galarneau, WI DNR.

PROTECTED BAY	Bedrock	Cobble	Sand
Previously dredged	91. Moonlight Bay 37. Egg Harbor	15. Little Sturgeon Bay 85. North Bay	100. Baileys Harbor
Undisturbed	31. Egg Harbor 93. Moonlight Bay	21. Sawyer Harbor	34. Egg Harbor 102. Baileys Harbor

EXPOSED (OPEN WATER)	Bedrock	Cobble	Sand
Previously dredged	52. Little Sister Bay 64. Sister Bay	47. Ephraim 69. Sister Bay	121. Egg Harbor 110. Whitefish Bay
Undisturbed	53. Little Sister Bay 63. Sister Bay	68. Sister Bay 48. Ephraim	<i>None Available</i>

In addition to the sites sampled for the three factors listed above, an additional set of 20 sites was selected to account for the potential added effects of piers on habitat conditions and biological communities in dredged and non-dredged areas (Table 2). These additional sites were sampled at least once during the summer.

Sampling Procedures at each Site:

Sample transect placement – Three sample transects were established at each site to provide coverage of the pertinent features of the location. Transects were oriented perpendicular to the shoreline and extended from just below the current water's edge to just beyond the depth of rooted macrophyte growth (Figure 1). At locations without any rooted macrophytes transects extended out 30 m from the water's edge.

Transects were spaced at five meter intervals along the shoreline at sites with no previous dredging history. At previously dredged locations one transect was situated in the center of the dredged channel, another on the sloped edge of the channel, and the third was placed next to the channel. This arrangement ensured incorporation into our study of known habitat heterogeneity derived from dredging activity.

Within each transect, samples and information were collected in three 10-m long regions located along the transect: 1) near-shore, 2) at the deepest end of the dredged area or at the deepest macrophyte depth at non-dredged sites, and 3) half way between the near-shore and deep ends of the transect.

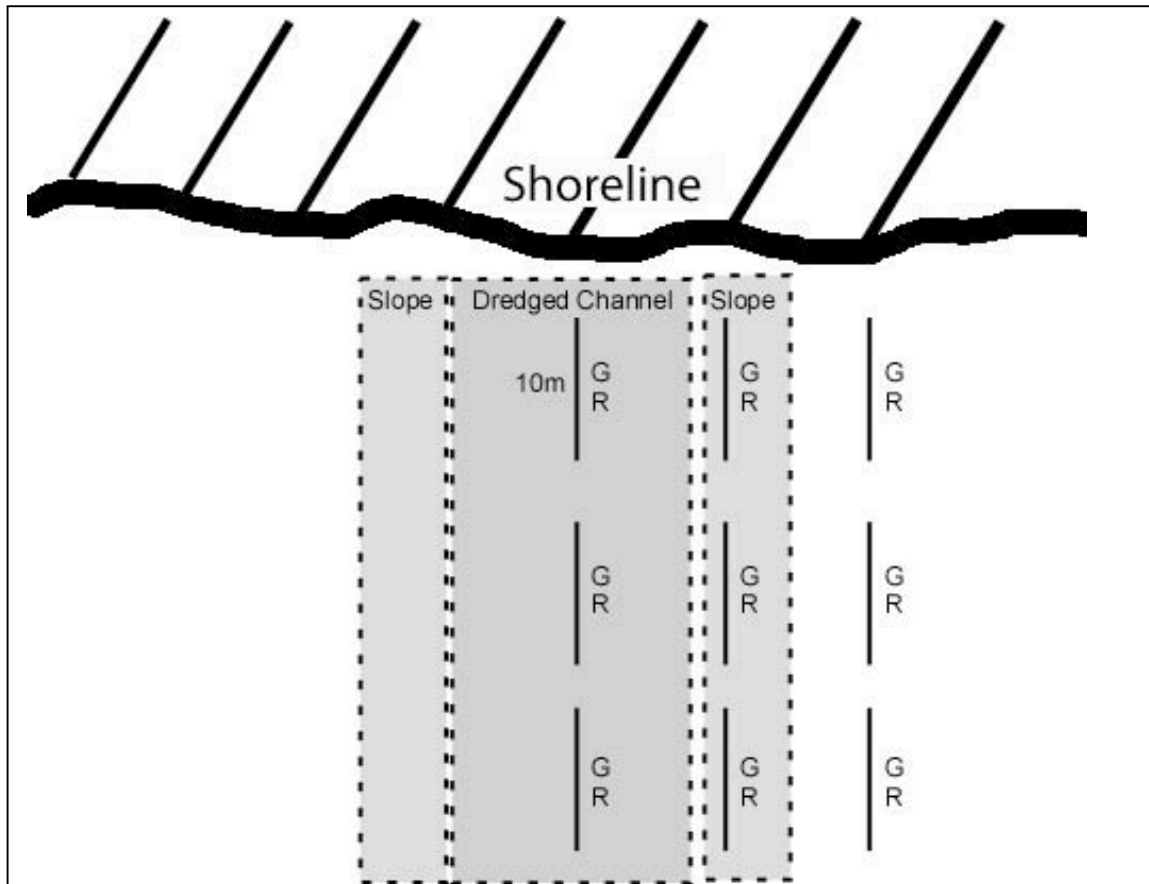


Figure 1. Diagram of transect placement and sample collection locations. The transects (each 10 m long) were laid perpendicular to the shoreline, spaced 5 m apart along the shoreline. Transects were placed in the middle of the channel, along the sloped edge of the channel, and just adjacent to the channel. Underwater video surveys were conducted along each 10 m transect. Duplicate grab samples (G) and duplicate vegetation rake samples (R) were collected near the middle of each transect. At sites that were not previously dredged the transects were placed similarly along the shoreline at the selected site.

Sediment characteristics – In each of the three regions along each transect duplicate sediment samples were collected using either an Ekman bottom grab sampler (0.15m X 0.15m box size) or by hand using a section of PVC pipe of equivalent area. Using either method approximately the top 10 cm of sediment was collected. In the field determinations were made by the same observer at all sites. Particle size determinations were made according to the Wentworth classification using a field particle comparison card (Appendix Table B1; Environment Canada 2002). Presence or absence of each particle size was assessed and used to determine the weighted average particle size for each sample. Particle shape was determined using a roundness scale ranging from 0 to 6 with higher values indicating rounder particles (Appendix Figure B1), and sediment colors were assessed against an even white background. Sediment odor was also noted if present.

Video transects – Video recording of each transect was performed while snorkeling or using SCUBA with a Sony 8mm video camera enclosed within an underwater camera housing. Weighted sections of plastic chain, 10 m long, were laid along each region of the transect as a guide. The camera was held approximately 0.5 m above the sediments providing a viewing diameter of at least 0.5 m of the benthic surface. Video surveys were conducted along each of the three regions of each transect. In the laboratory, the videos were converted to digital files using a Memorex DVD recorder. Digital still images from the DVD were analyzed to determine area coverage characteristics. Ten images, evenly spaced at 1 m intervals along the chain recorded in each region of

transects, were quantified for surface characteristics. Each still image was quantified by securing a transparency printed with a 10-by-10 grid over the image displayed on the TV monitor. Each of the resulting 100 squares was assessed and classified as consisting of one of four types: 1) bare rock, 2) sediment, 3) attached benthic algae, and 4) macrophytes. Classification was determined as the majority coverage of the four types in a given square. The resulting data provided an estimate of the percent coverage for the image of the four surface types.

Aquatic vegetation sampling – In addition to the percent coverage data derived from the video transects, aquatic vegetation was also assessed using a standard rake sampling procedure (Deppe & Lathrop 1992). A weighted double-headed rake was pulled approximately 2 m along the bottom at each location. The rake was 35 cm wide, contained 14 teeth on each side, each of which was 5 cm long. Duplicate rake samples were collected near the center of each region along transects, producing 18 rake samples were site. Rake fullness was determined using a 0-3 fullness scale (Herman 2007): 0= no vegetation on teeth, 1=a few plants on rake head, 2=rake head approximately half full, and 3=rake head full or overflowing.

All specimens recovered in rake sampling were identified to the species level using standard keys and photographs (Fasset 1957, Voss 1985, Borman et al. 1997). Additional visual surveys were conducted to assemble a complete species list of emergent, floating and submerged and attached vegetation at each site.

Benthic macroinvertebrate sampling: The composition and abundance of the benthic macroinvertebrates was determined primarily in the grab samples used to determine sediment particle characteristics. In the laboratory the complete grab sample was examined for macroinvertebrates. Individuals were categorized into broad taxonomic groupings using Pennak (1989), Merritt and Cummins (1996), and Thorp and Covich (1991). Abundance was determined using a scale from 0 – 4: 0=no individuals observed, 1=one individual observed, 2=2 - 10 individuals observed, 3=11 – 99 individuals observed, and 4=100 or more individuals observed in a sample.

Data Handling and Statistical Analysis:

Field data were recorded on waterproof sampling field data sheets. Data were later checked for completeness and accuracy. Data obtained in the laboratory were entered into project lab notebooks. Data were later entered into Microsoft Excel spreadsheets for initial summary and analysis. Further statistical analysis was performed using the SPSS software package (ver. 16.0).

Data were tested for heteroscedasticity, kurtosis, and normality. If needed, data were transformed with an appropriate procedure prior to conducting ANOVA tests. A full factorial ANOVA (Type III) was run initially on the full data set. When significant interactions were observed separate ANOVA tests were conducted on parsed data according to the appropriate treatment categories. Hierarchical classification (i.e. cluster) analysis was used to determine natural grouping of sites based on macrophyte and macroinvertebrate data. Derived groupings were then compared to experimental treatment characteristics (i.e. dredging history, substrate type, and site exposure).

Results

Video Surveys of Transects:

Results from video surveys of the three transect lines established at each site show clear differences among sites located on different substrate types as well as among sites with differing dredging history (Figure 2). Sites in protected areas with bedrock as the main substrate had over 50% of the area as bare rock, with an additional 20 – 30% as sediment without vegetation. There was an additional 20% of the area in both previously dredged and undisturbed sites covered by benthic algae (primarily *Cladophora*). On bedrock substrate, macrophytes were only found in non-dredged sites. In contrast, at locations with cobble substrates the coverage by benthic algae and macrophytes was reversed, with 10 - 15% of the area covered by macrophytes and essentially no benthic algae. Similarly, at sites with sand as the primary substrate, macrophytes were found on 15 – 35% of the area with essentially no benthic algae observed. Macrophytes covered a higher percentage of the area at dredged sites than at non-dredged sites in the sandy substrate locations.

As expected from these overall patterns, the video survey data demonstrated that there are significant effects of all factors and interactions in the full data set ($P < 0.01$ for all effects). Separate analyses based on each factor show that macrophyte coverage is significantly affected by previous dredging at sites with substrate types of bedrock or sand (Table 3, P-values less than 0.05). However, the effects of dredging had opposite effects at these two types of sites. More macrophytes were found on non-dredged areas on bedrock substrate while dredged areas showed more macrophytes at sites with a sand substrate (Figure 2 & 3a). Benthic algae coverage did not differ significantly at bedrock

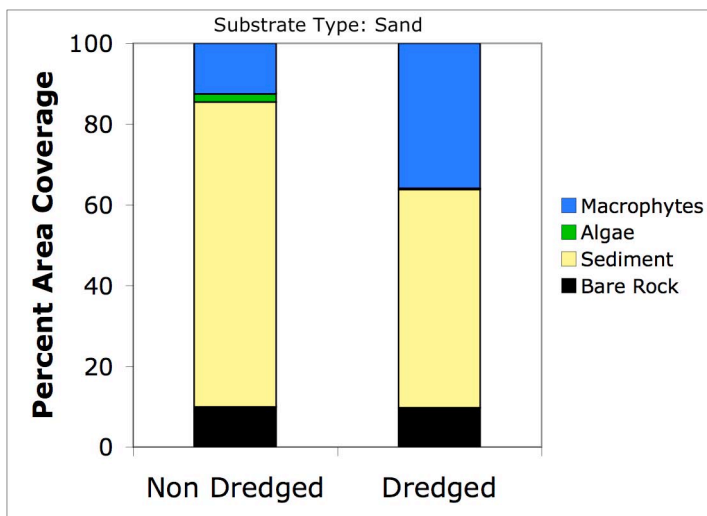
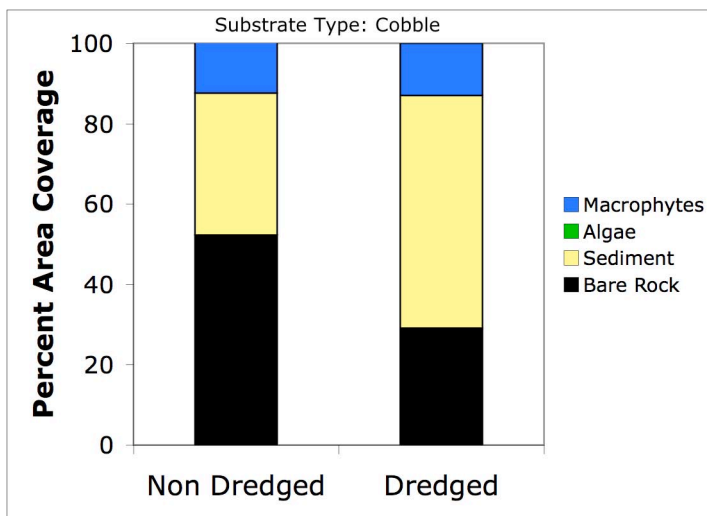
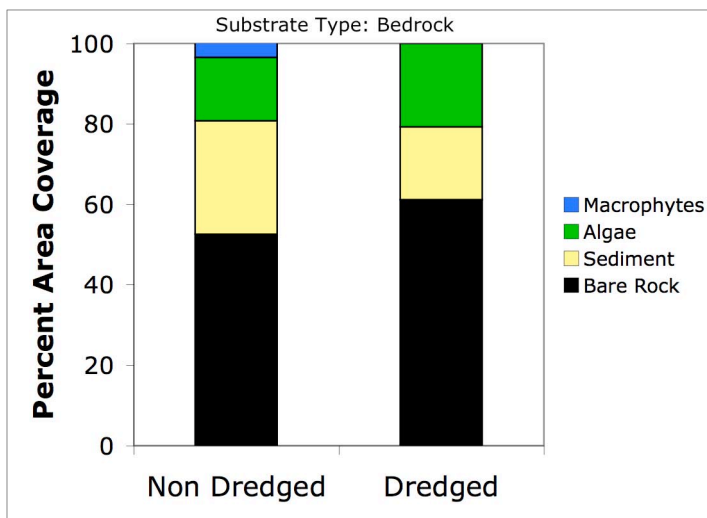


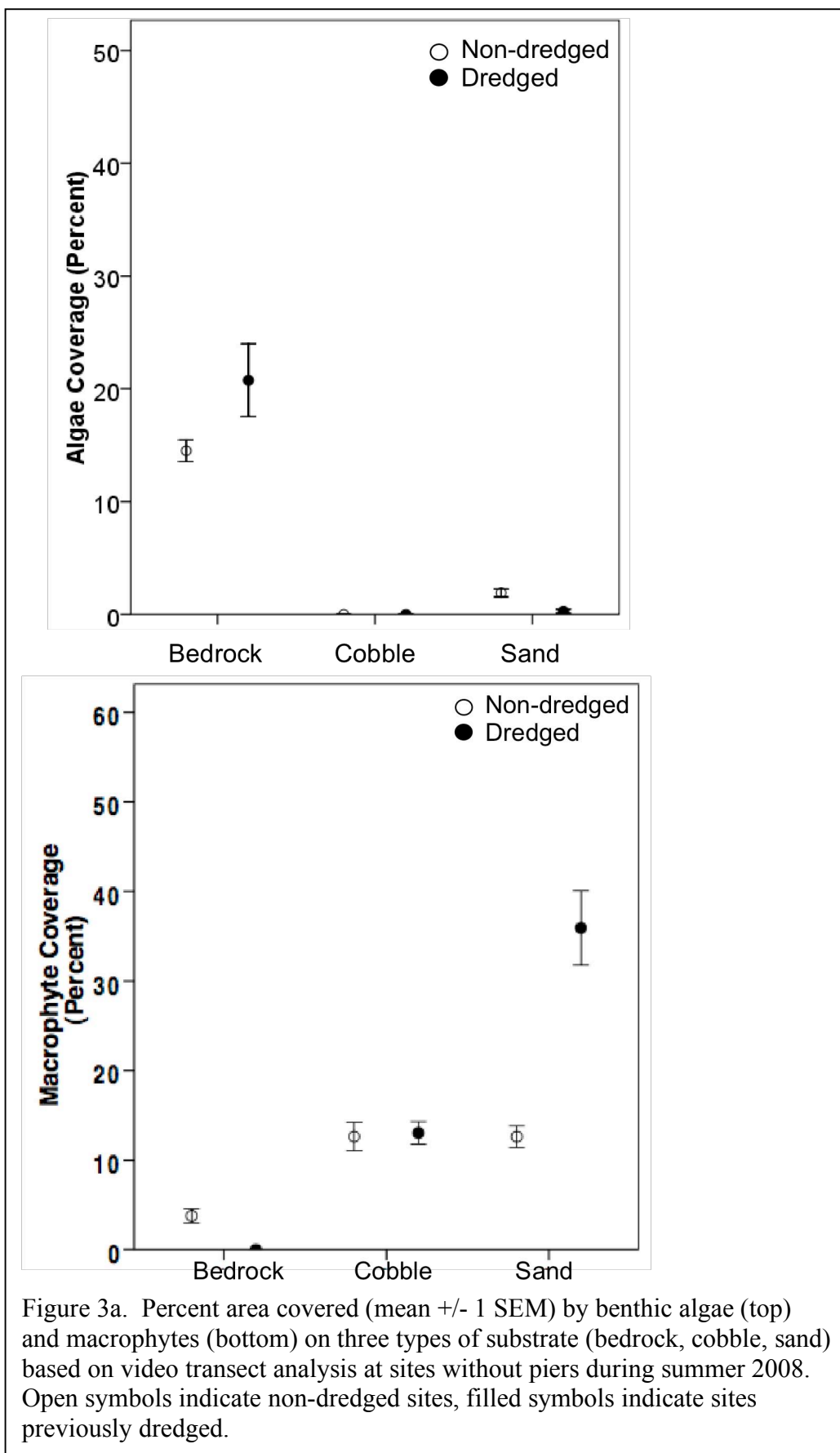
Figure 2. Mean percent area covered by bare rock, sediment, macrophytes and benthic algae estimated by video surveys at sites with bedrock (top), cobble (middle), and sand (bottom) substrate types at protected sites during summer 2008.

Table 3. Analysis of Variance (ANOVA) results for separate tests of the effects of dredging on the area coverage of benthic algae, macrophytes, sediment, and bare rock for protected sites with no piers during summer 2008. Values in table indicate the P-value for the between treatment effect in a one-way ANOVA. Significant effects of dredging on variables are indicated with asterisks (*=significant, **=highly significant).

Variable Measured	Bedrock (df=1,88)	Cobble (df=1,58)	Sand (df=1,178)
Algae	0.101	None	0.002 **
Macrophytes	0.001 **	0.844	<0.001 **
Sediment	0.005 **	<0.001 **	<0.001 **
Bare Rock	0.053	<0.001 **	0.947

Table 4. One way analysis of variance (ANOVA) results for separate tests of the effects of Channel Position on area coverage estimated by video surveys for algae, macrophytes, sediment and bare rock on dredged sites in protected areas. The data employed are for sites without piers. Significant effects of Channel Position on each variable are indicated with asterisks (*=significant, **=highly significant).

Dependent Variable	df	Mean Square	F-ratio	P-value
Algae	2,117	858.43	5.937	0.004 **
Macrophytes	2,117	3890.78	5.499	0.005 **
Sediment	2,117	4163.23	3.924	0.022 *
Bare Rock	2,117	1827.33	2.012	0.138



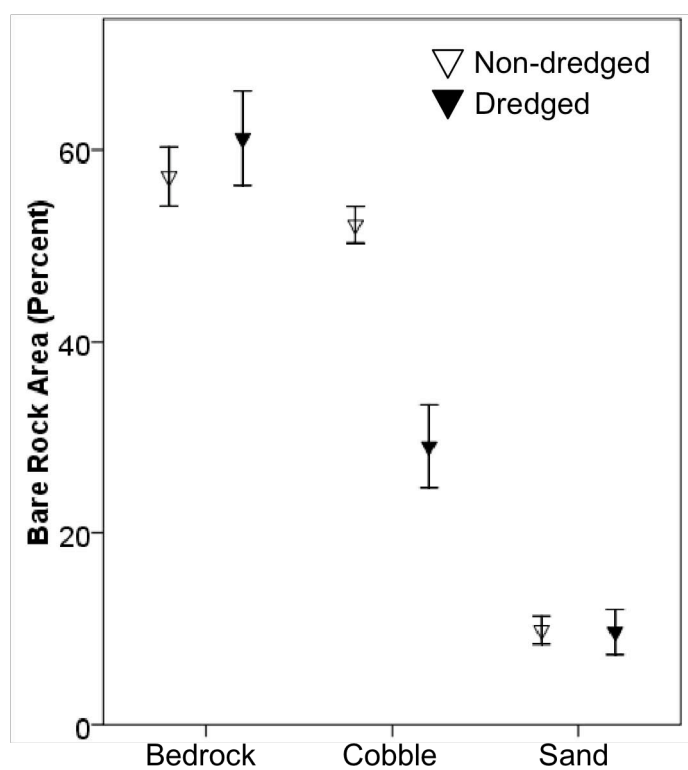
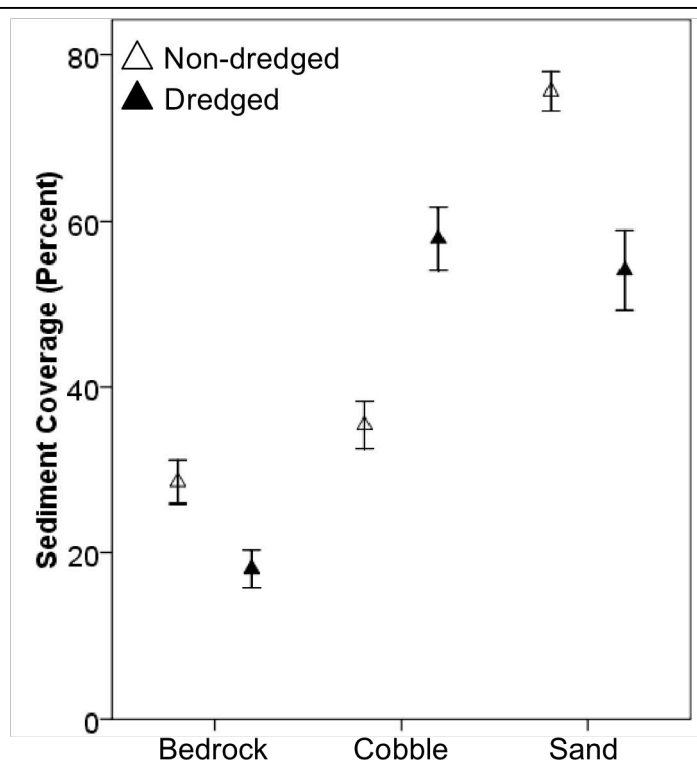
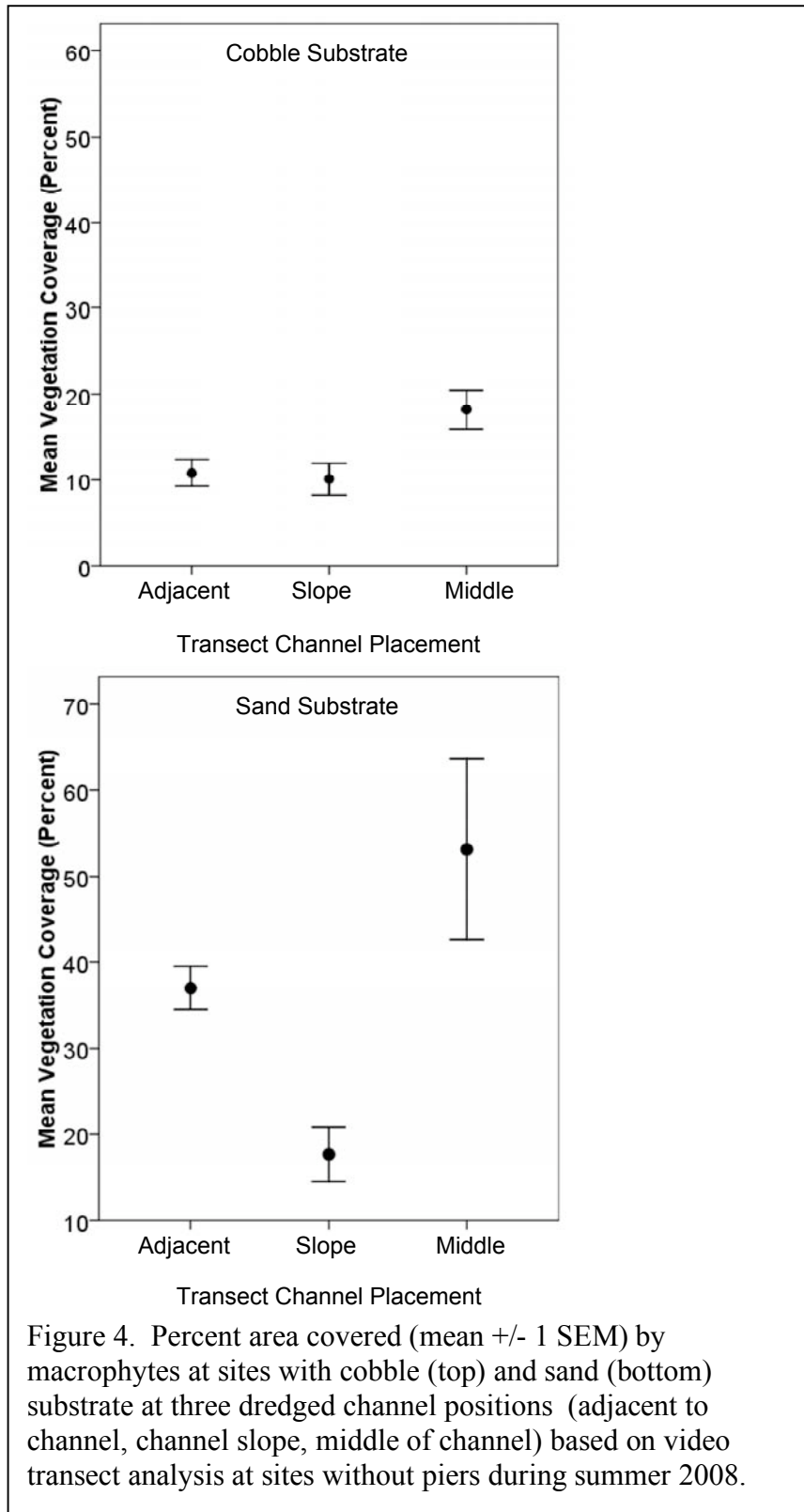


Figure 3b. Percent area covered (mean \pm 1 SEM) by sediment (top) and bare rock (bottom) on three types of substrate (bedrock, cobble, sand) based on video transect analysis at sites without piers during summer 2008. Open symbols indicate non-dredged sites, filled symbols indicate sites previously dredged.

or cobble sites, but algae was significantly higher at non-dredged sites with a sandy substrate (Figures 2 & 3a). Finally, dredging significantly changed the relative area of coverage on all three types of substrate; 1) on bedrock sites dredging resulted in higher benthic algae and bare rock coverage and less sediment and macrophyte area, 2) at cobble sites there was significantly higher sediment and lower bare rock coverage, and 3) on sandy substrate, dredged locations had significantly higher area coverage by macrophytes and lower benthic algae and sediment coverage (Figures 2 & 3).

Dredged channels displayed significant differences in bottom coverage compared to adjacent non-dredged areas, as indicated by the significant effects of Channel Position on coverage by benthic algae, macrophytes and sediment observed in the ANOVAs for each variable (Table 4). The middle of channels had significantly higher macrophyte coverage than adjacent areas in both cobble and sand substrate locations (Figure 4), most likely due to increased amounts of smaller grained sediment in the channels (see below). Locations with bedrock substrate had essentially no macrophyte growth overall (Figures 2 & 3). Although overall benthic algae coverage was approximately the same at dredged and nondredged sites with a bedrock substrate (20% coverage when all transects are averaged), there was significantly less benthic algae in the middle of dredged channels compared to adjacent areas at bedrock sites (Figure 5). Benthic algae coverage in the transects adjacent to the channel also was dramatically higher than at the non-dredged sites, indicating that dredging has lasting impacts on the areas outside of the channel as well (Figure 5; adjacent transects = 42.5 ± 14.08 , non-dredged sites = 15.72 ± 1.44). At the sites with bedrock, area covered by sediment and bare rock was higher in the middle



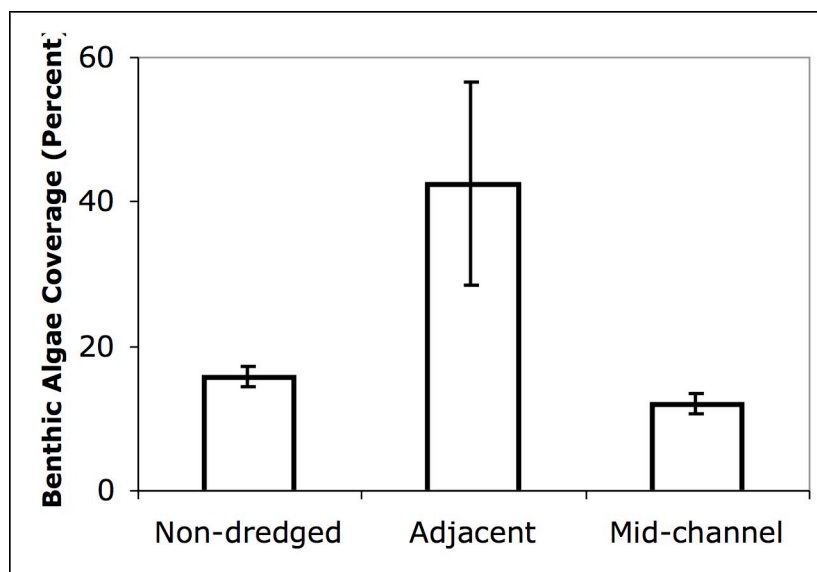


Figure 5. Percent area covered (mean \pm 1 SEM) by benthic algae at sites with bedrock substrate adjacent to dredged channel, in the middle of channel, and at non-dredged sites. Data are based on video transect analysis at sites without piers during summer 2008.

Table 5. Analysis of variance (ANOVA) results for the full dataset on sediment particle size. A Type III ANOVA model was employed for this analysis. Significant effects of source factors are indicated with asterisks (*=significant, **=highly significant).

Source	df	Significance Level
Dredge	1	0.001 **
Substrate Type	2	0.001 **
Exposure	1	0.001 **
Dredge X Substrate	2	0.145
Dredge X Exposure	1	0.192
Substrate X Exposure	2	0.001 **
Dredge X Substrate X Exposure	2	0.001 **

of channels (88.1% +/- 2.25) than in adjacent areas (57.5% +/- 4.03), indicating that dredging modifies the habitat in terms of sediment as well as biotic relationships.

Particle Size Analysis:

There were clear effects of Dredging, Substrate type and site Exposure on the size distribution of particles observed during the study. Analysis of variance on the full dataset indicated that each of these factors had highly significant effects on particle size, but that there were also significant interaction effects between all three factors (Table 5). Essentially the same results occurred when only non-pier sites were included in the analysis. The only difference was that the interaction terms (Dredge X Substrate) and (Dredge X Exposure) had P-values of 0.067 and 0.001 respectively. Due to the significant interaction effects, the data were parsed and analyzed separately to determine the effects of Dredging history according to Substrate type and Exposure level and the differences within dredged channels compared to area adjacent to the channels.

Particle size was significantly smaller in the middle of the dredged channel than at either the slope or adjacent to the channel (Figure 6, Table 6). A shift from an average grain size of over 6 (gravel and very coarse sand particles, 2-5 mm) to 4.5 (medium sized sand, 0.25 – 0.5 mm) occurred in moving from the undisturbed sites adjacent to the dredged channel into the middle of the channel. Particles in the middle of the channel were significantly smaller compared to those either on the sloping sides of the channel (LSD posthoc test; $P=0.003$) or in the adjacent areas ($P<0.001$). In addition, only the middle of channels contained measurable amounts of the smallest particles observed (silt,

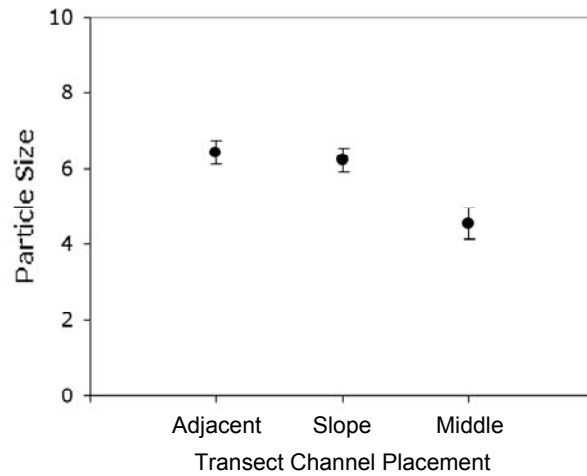


Figure 6. Sediment particle grain size (mean +/- 1 SEM) in grab samples from dredged sites without a pier at three positions relative to three dredged channel positions (adjacent to channel, channel slope, middle of channel) during summer 2008.

Table 6. One way analysis of variance (ANOVA) results for effects of Channel Position on sediment particle size. The data employed are for sites without piers and that had been dredged previously. The highly significant effect of Channel Position is indicated with asterisks.

Source	Sum of Squares	df	Mean Square	F-ratio	P-value
Between Groups	83.676	2	41.838	8.709	<0.001 **
Within Groups	759.003	158	4.804		
Total	842.679	160			

Table 7. One way analysis of variance (ANOVA) results for separate tests of the effects of Dredge history on sediment particle size. The data employed are for sites without piers. Significant effects of dredging for each Exposure/Substrate combination are indicated with asterisks (*=significant, **=highly significant).

Exposure	Substrate Type	df	Mean Square	F-ratio	P-value
Exposed	Bedrock	1	24.465	2.979	0.093
Exposed	Cobble	1	1.805	0.747	0.391
Exposed	Sand	1	20.382	3.779	0.066
Protected	Bedrock	1	16.441	4.811	0.033 *
Protected	Cobble	1	22.927	10.947	0.002 **
Protected	Sand	1	5.096	1.348	0.251

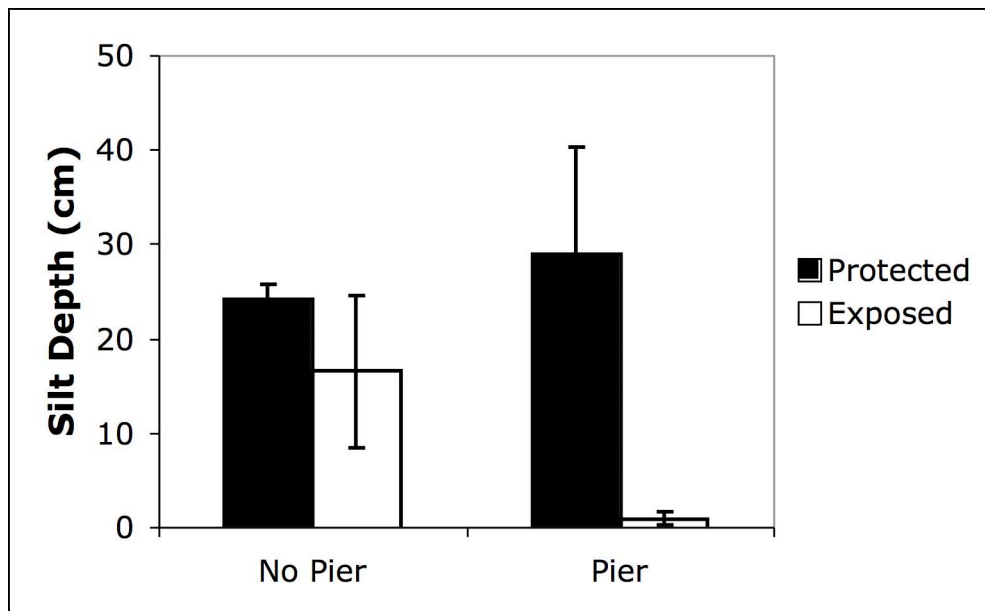


Figure 7. Depth of silt (mean \pm 1 SEM) in the middle of dredged channels at sites without piers or with piers, in protected and exposed locations during summer 2008.

grain size < 0.063 mm). The depth of silt in the middle of the channels varied from 0 to 76 cm, and tended to be deepest in the protected areas (Figure 7).

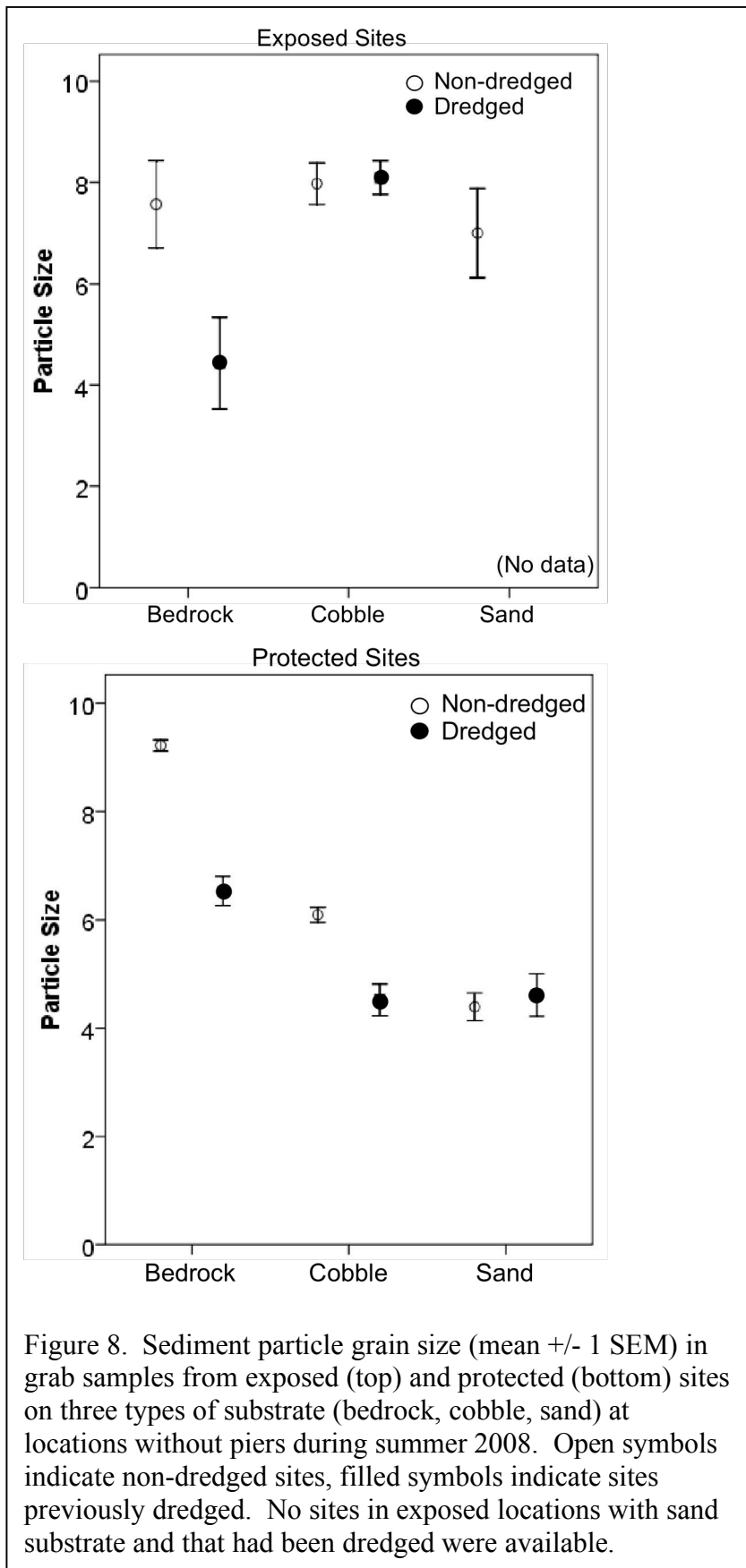
A higher abundance of smaller sized particles at protected sites was also reflected in the significant differences among dredged and non-dredged sites with bedrock and cobble substrates (Table 7, Figure 8). There was a similar trend at sites with bedrock in exposed areas, but the effects of dredging there were only marginally significant ($P=0.093$; Figure 8). At sites with piers, significantly smaller particles occurred at previously dredged sites on sandy substrates also (Figure 9). Overall, particle size was generally smaller at protected sites and at previously dredged locations.

Particle Shape, Color and Odor:

The shape of particles was significantly affected by Dredge history at exposed cobble areas and at protected locations with all three types of substrate (Table 8). Particles were typically more rounded at dredged sites than at sites with no previous dredging history, as demonstrated by higher shape values at previously dredged locations (Figure 10). There was no significant effect of position in channels on shape measures ($P>0.5$) but sediments in the middle of dredged channels were the only place where black silt was observed and the only sediments that emitted a distinct odor of hydrogen sulfide (e.g. rotten eggs).

Vegetation Composition Analysis:

A total of 24 taxa of vegetation (macrophytes plus benthic macroalgae) were recorded at the sites studied (Table 9). Eight of the species occurred in more than 10% of all the sites sampled. Among these eight widespread groups are two species that are



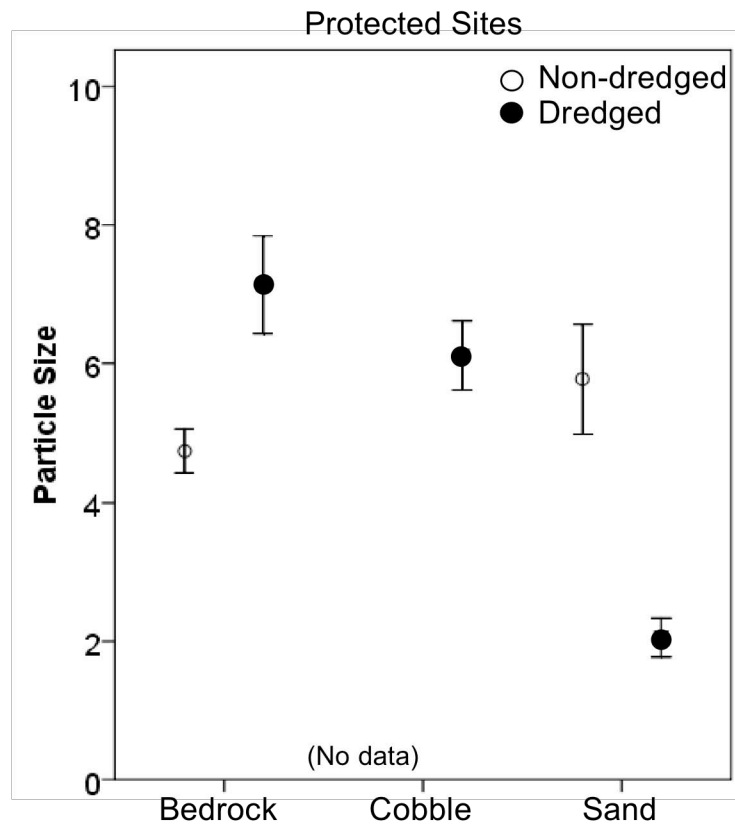


Figure 9. Sediment particle grain size (mean \pm 1 SEM) in grab samples from protected sites on three types of substrate (bedrock, cobble, sand) at locations with piers during summer 2008. Open symbols indicate non-dredged sites, filled symbols indicate sites previously dredged. No data were obtained for sites on cobble substrate that had not been dredged.

Table 8. One way analysis of variance (ANOVA) results for separate tests of the effects of Dredge history on sediment particle shape. The data employed are for sites without piers. Significant effects of dredging for each Exposure/Substrate combination are indicated with asterisks (*=significant, **=highly significant).

Exposure	Substrate Type	df	Mean Square	F-ratio	P-value
Exposed	Bedrock	1	0.333	1.000	0.423
Exposed	Cobble	1	2.025	7.043	0.017 *
Exposed	Sand	1	No data		
Protected	Bedrock	1	0.409	7.364	0.024 *
Protected	Cobble	1	1.071	4.197	0.045 *
Protected	Sand	1	2.575	16.644	<0.001 **

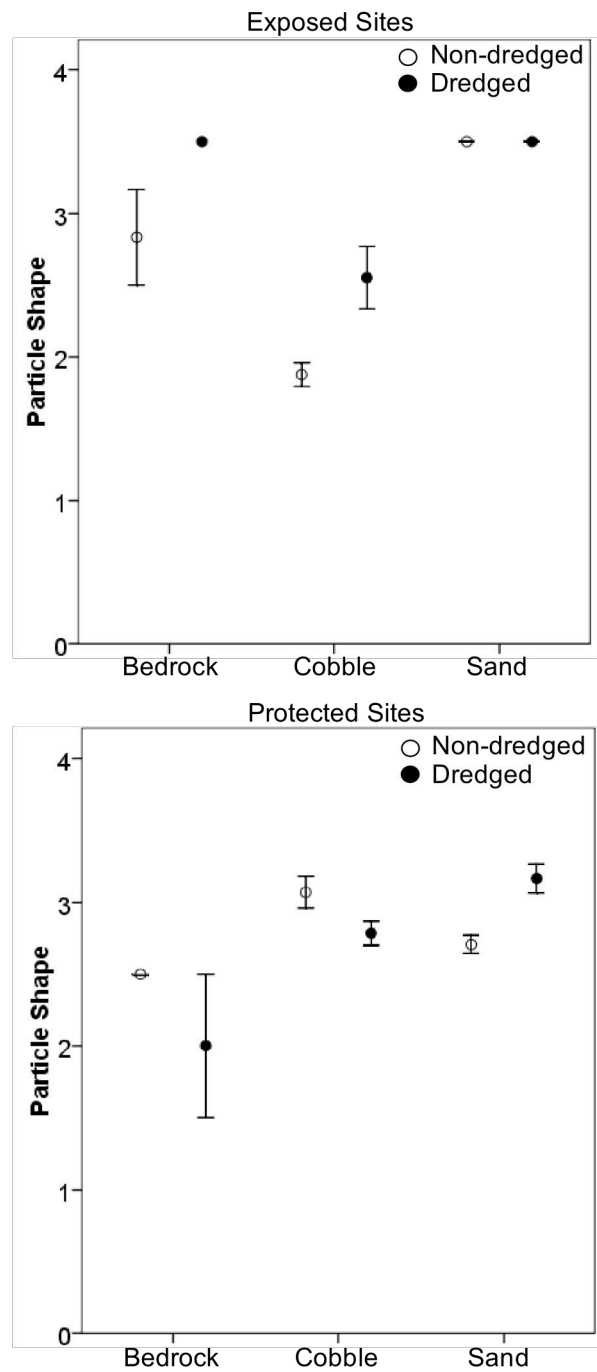


Figure 10. Sediment particle shape (mean \pm 1 SEM) in grab samples from exposed (top) and protected (bottom) sites on three types of substrate (bedrock, cobble, sand) during summer 2008. Open symbols indicate non-dredged sites, filled symbols indicate sites previously dredged. Higher shape value indicated more rounded particles.

Table 9a. Composition of vegetation observed at sites along the Green Bay shoreline of Door County, WI during summer 2008. Presence of taxa during at least one of the sampling days is indicated by the value 1. Aquatic invasive species are highlighted. Site numbers for dredged sites are in bold italics. See Table A1 and Figure A1 for site location details.

Taxa	11	12	15	16	17	21	23	24	30	31	33	34	37	44	45	47	48	52	53	63	64	65	68	69
<i>Carex comosa</i> , Bristly sedge																								
<i>Ceratophyllum demersum</i> , Coontail									1															
<i>Ceratophyllum echinatum</i> , Spiny hornwort							1																	
<i>Chara coronata</i> , Muskgrass			1	1	1	1	1			1		1		1	1	1	1	1				1	1	1
<i>Cladophora</i> sp.	1	1		1		1		1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
<i>Elodea canadensis</i> , Common waterweed			1			1	1																	
<i>Heteranthera dubia</i> , Water star-grass																								
<i>Juncus effusus</i> , Soft rush																								
<i>Myriophyllum spicatum</i> , Eurasian water-milfoil			1	1	1	1	1	1	1			1	1		1	1	1	1			1	1	1	1
<i>Potamogeton crispus</i> , Curly-leaf pondweed				1	1	1	1		1												1			1
<i>Potamogeton diversifolius</i> , Water-thread pondweed							1																	
<i>Potamogeton richardsonii</i> , Claspig-leaf pondweed					1	1						1												
<i>Potamogeton zosteriformis</i> , Flat-stem pondweed				1	1	1	1								1	1	1	1	1			1	1	
<i>Najas flexilis</i> , Bushy pondweed						1	1																	
<i>Ranunculus flammula</i> , Creeping spearwort																								
<i>Ruppia cirrhosa</i> , Ditch grass																								
<i>Sagittaria brevirostra</i> , Midwestern arrowhead																								
<i>Schoenoplectus pungens</i> , Three-square																								
<i>Schoenoplectus subterminalis</i> , Water bulrush										1				1		1		1					1	
<i>Scirpus americanus</i> , Chair-makers rush																								
<i>Spirogyra</i> sp./ <i>Spirotaenia</i> sp.																								
<i>Stuckenia pectinata</i> , Sago pondweed			1		1	1						1				1	1	1				1	1	
<i>Vallisneria americana</i> , Wild celery			1	1	1	1	1	1				1				1	1					1		1
<i>Zannichellia palustris</i> , Horned pondweed																								
Total Taxa	1	1	5	6	7	10	9	3	4	2	1	6	2	2	4	7	6	6	2	1	3	6	6	5

Table 9b. Composition of vegetation observed at sites along the Lake Michigan shoreline of Door County, WI during summer 2008. Presence of taxa during at least one of the sampling days is indicated by the value 1. Aquatic invasive species are highlighted. Site numbers for dredged sites are in bold italics. See Table A1 and Figure A1 for site location details.

Taxa	71	72	80	81	83	84	85	90	91	92	93	100	101	102	110	111	112	113	120	121
<i>Carex comosa</i> , Bristly sedge						1														
<i>Ceratophyllum demersum</i> , Coontail																				
<i>Ceratophyllum echinatum</i> , Spiny hornwort																				
<i>Chara coronata</i> , Muskgrass	1	1	1	1	1	1	1			1	1								1	
<i>Cladophora</i> sp.					1	1	1	1	1	1				1	1	1		1	1	1
<i>Elodea canadensis</i> , Common waterweed																				
<i>Heteranthera dubia</i> , Water star-grass												1								
<i>Juncus effusus</i> , Soft rush											1									
<i>Myriophyllum spicatum</i> , Eurasian water-milfoil	1	1	1	1		1		1		1										1
<i>Potamogeton crispus</i> , Curly-leaf pondweed		1						1											1	
<i>Potamogeton diversifolius</i> , Water-thread pondweed																				
<i>Potamogeton richardsonii</i> , Claspingleaf pondweed		1																		
<i>Potamogeton zosteriformis</i> , Flat-stem pondweed	1	1		1		1													1	1
<i>Najas flexilis</i> , Bushy pondweed																				
<i>Ranunculus flammula</i> , Creeping spearwort		1																		
<i>Ruppia cirrhosa</i> , Ditch grass	1										1			1						
<i>Sagittaria brevirostra</i> , Midwestern arrowhead						1														
<i>Schoenoplectus pungens</i> , Three-square						1														
<i>Schoenoplectus subterminalis</i> , Water bulrush			1	1	1	1													1	
<i>Scirpus americanus</i> , Chair-makers rush						1														
<i>Spirogyra</i> sp. / <i>Spirotaenia</i> sp.															1	1				
<i>Stuckenia pectinata</i> , Sago pondweed																			1	
<i>Vallisneria americana</i> , Wild celery		1		1		1														
<i>Zannichellia palustris</i> , Horned pondweed	1																			
Total Taxa	5	7	3	5	3	10	2	3	1	3	3	1	1	2	2	1	1	1	6	3

considered aquatic invasive species (Table 10). *Myriophyllum spicatum* (Eurasian water-milfoil) was recorded in 56.8% of the sites and *Potamogeton crispus* (Curly-leaf pondweed) occurred at almost a quarter of the locations sampled. Of the 10 sites with Curly-leaf pondweed 7 had been previously dredged, suggesting that disturbance at dredged areas may contribute to the increased prevalence of invasive species. The nuisance macroalgae *Cladophora* sp. was observed at over 70% of the sites studied.

Vegetation richness (i.e. number of species) was generally higher at previously dredged sites (Figure 11). The only sites with more than six species present were sites with a dredging history (except for one site at Sawyer Harbor with a solid Pier). At sites without piers there was a significantly higher number of plant species at dredged (mean = 6.7 species) compared to nondredged sites (mean = 3.1 species; t-test $P=0.019$, $df=8$). There was no statistically significant difference due to dredging history at sites with a pier present ($P>0.05$, $df=8$).

Based on vegetation composition sites could be clustered according to previous dredge history. By grouping sites based on similarities of species composition, clustering analysis can suggest “natural” assemblages that arise from the vegetation analysis. There were three natural groupings of sites defined by the cluster analysis using data for sites with piers (Figure 12). The sites connected by low “dissimilarity” on the dendrogram have similar vegetation composition and share species in common. The most closely related set of sites based on species composition were seven sites that had no previous dredging history (Nondredged Grouping 1). All of these sites had no macrophytes and only benthic algae as the resident vegetation (Table 11). A second set of nondredged sites (9 total) was also identified, and had a more diverse plant association that included

Table 10. Percent of all sites where vegetation taxa were observed for sites with values greater than 10%. Aquatic invasive species are highlighted.

Taxa	Occurrence (Percent)
<i>Cladophora</i> sp.	72.7
<i>Chara coronata</i> , Muskgrass	56.8
<i>Myriophyllum spicatum</i> , Eurasian water-milfoil	56.8
<i>Potamogeton zosteriformis</i> , Flat-stem pondweed	38.6
<i>Vallisneria americana</i> , Wild celery	31.8
<i>Potamogeton crispus</i> , Curly-leaf pondweed	22.7
<i>Schoenoplectus subterminalis</i> , Water bulrush	22.7
<i>Stuckenia pectinata</i> , Sago pondweed	22.7

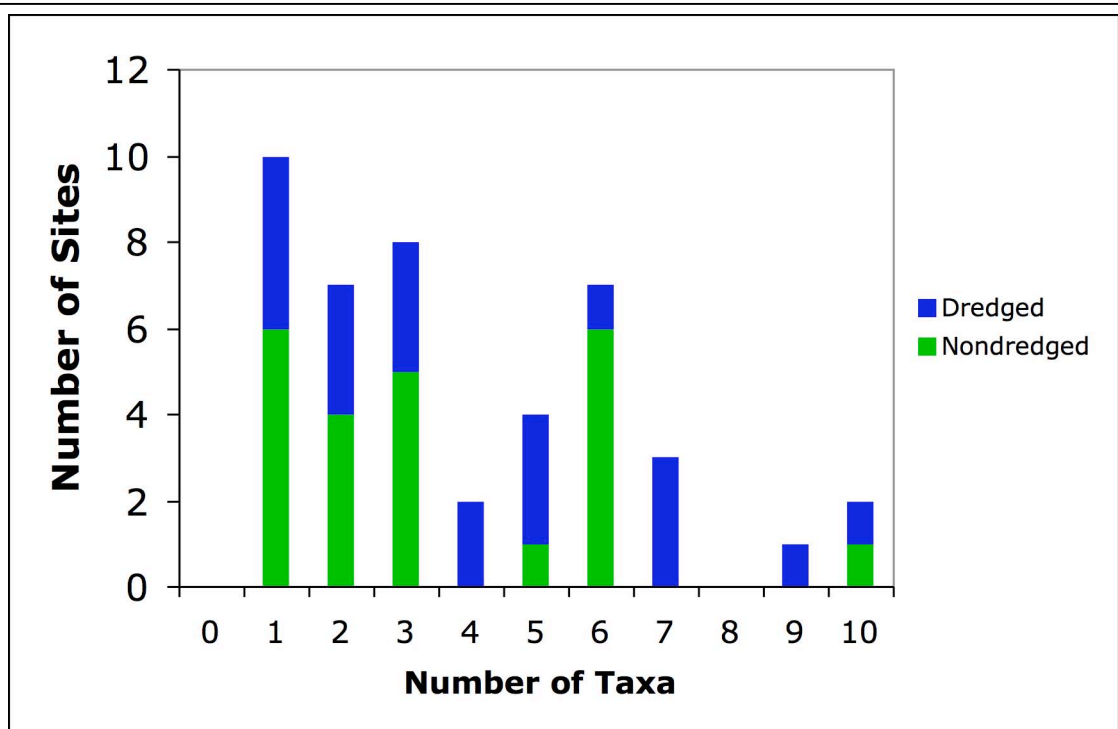


Figure 11. Number of macrophyte and benthic algae taxa recorded at dredged and nondredged sites during the summer of 2008.

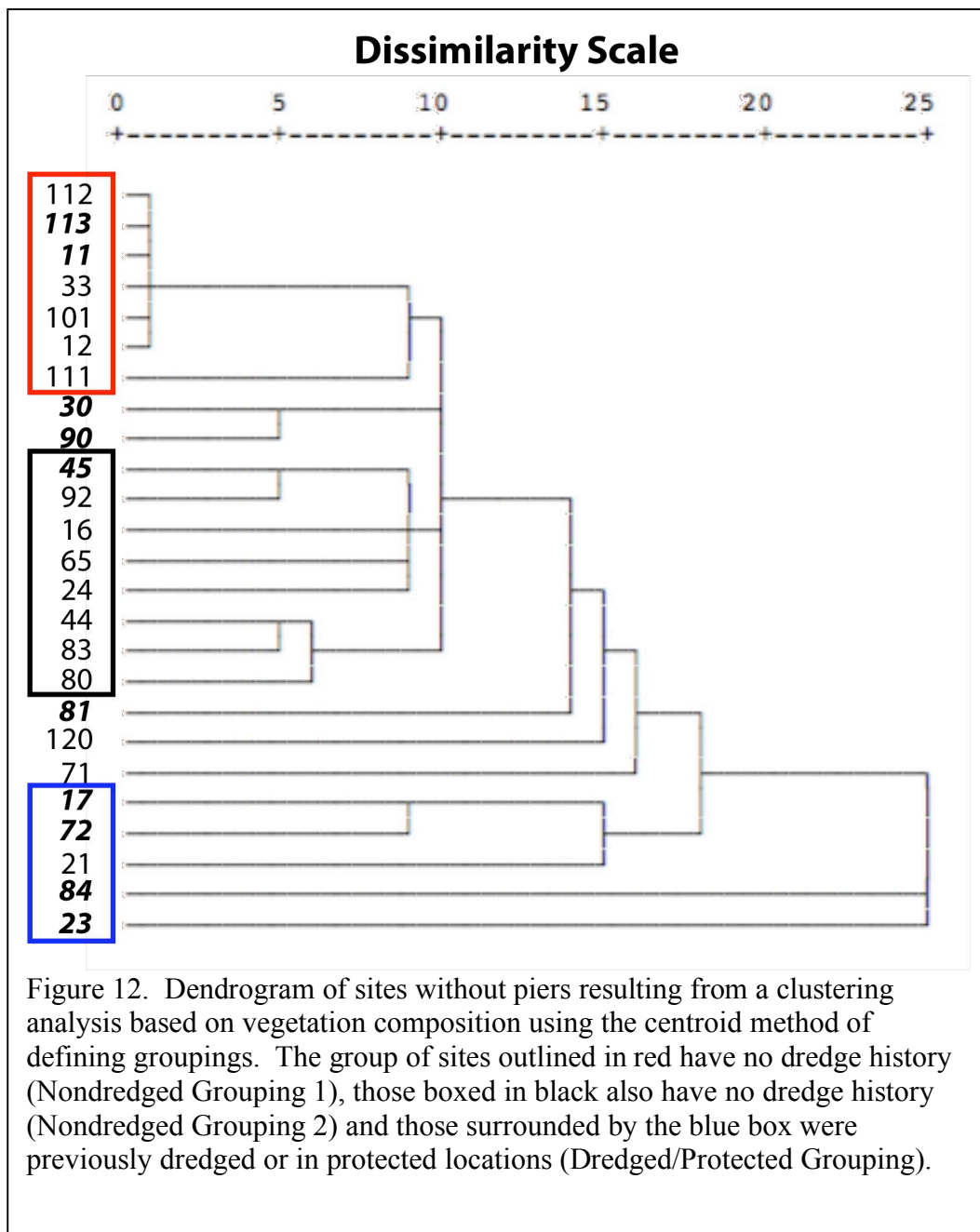


Table 11. Plant associations observed at sites in groupings defined by cluster analysis using a centroid agglomerative method.

Results for Sites without Piers:

Dredged/Protected Sites Grouping

Chara coronata, Muskgrass
Elodea canadensis, Common waterweed
Myriophyllum spicatum, Eurasian water-milfoil
Potamogeton crispus, Curly-leaf pondweed
Potamogeton richardsonii, Claspingleaf pondweed
Potamogeton zosteriformis, Flat-stem pondweed

Nondredged Grouping 1

Cladophora sp.
Spirogyra sp./*Spirotaenia* sp.

Nondredged Grouping 2

Chara coronata, Muskgrass
Cladophora sp.
Myriophyllum spicatum, Eurasian water-milfoil
Potamogeton zosteriformis, Flat-stem pondweed
Schoenoplectus subterminalis, Water bulrush
Vallisneria americana, Wild celery

Results for Sites with Piers:

Dredged Grouping

Chara coronata, Muskgrass
Cladophora sp.
Myriophyllum spicatum, Eurasian water-milfoil
Potamogeton crispus, Curly-leaf pondweed

Bedrock/Sand Grouping

Chara coronata, Muskgrass
Cladophora sp.
Potamogeton zosteriformis, Flat-stem pondweed
Ruppia cirrhosa, Ditch grass

Cobble Grouping

Chara coronata, Muskgrass
Cladophora sp.
Myriophyllum spicatum, Eurasian water-milfoil
Potamogeton zosteriformis, Flat-stem pondweed
Schoenoplectus subterminalis, Water bulrush
Stuckenia pectinata, Sago pondweed
Vallisneria americana, Wild celery

Cladophora and Eurasian water-milfoil, but also Wild celery, Muskgrass, and Water bulrush. Finally, the third grouping contained previously dredged sites that included both invasive plant species (Eurasian water-milfoil and Curly-leaf pondweed) and four other native species.

Similar groupings were derived for sites with piers. There were three clear groupings with this dataset also, based on dredging history and substrate type (Figure 13). Locations with cobble substrate clustered together, as did sites with bedrock and sand. The plant associations in these sites were very similar to the associations defined with the nonpier sites, with the species list for the cobble group being identical except for one species to that observed in the Nondredged Grouping 2 from the nonpier data (Table 11). Sago pondweed was found at all sites in the Cobble Grouping with piers, but not in the nonpier sites included in the Nondredged Grouping 2 set. The dredged groupings in both datasets were very similar, containing Muskgrass, Eurasian water-milfoil, and Curly-leaf pondweed. Finding the same associations of vegetation in dredged grouping in both pier and non-pier data indicates that in this study dredging generally leads to similar vegetation communities that are distinct from those found in non-dredged areas.

Vegetation Abundance Analysis:

There were significant effects of dredging on vegetation abundance, as measured by rake density sampling, in both the exposed and protected sites (Table 12). On cobble substrate in locations without piers rake density was significantly higher in previously dredged than non-dredged sites (Figure 14). We did not have any sites with sand substrate and no pier that had been dredged, so it was not possible to assess effects for

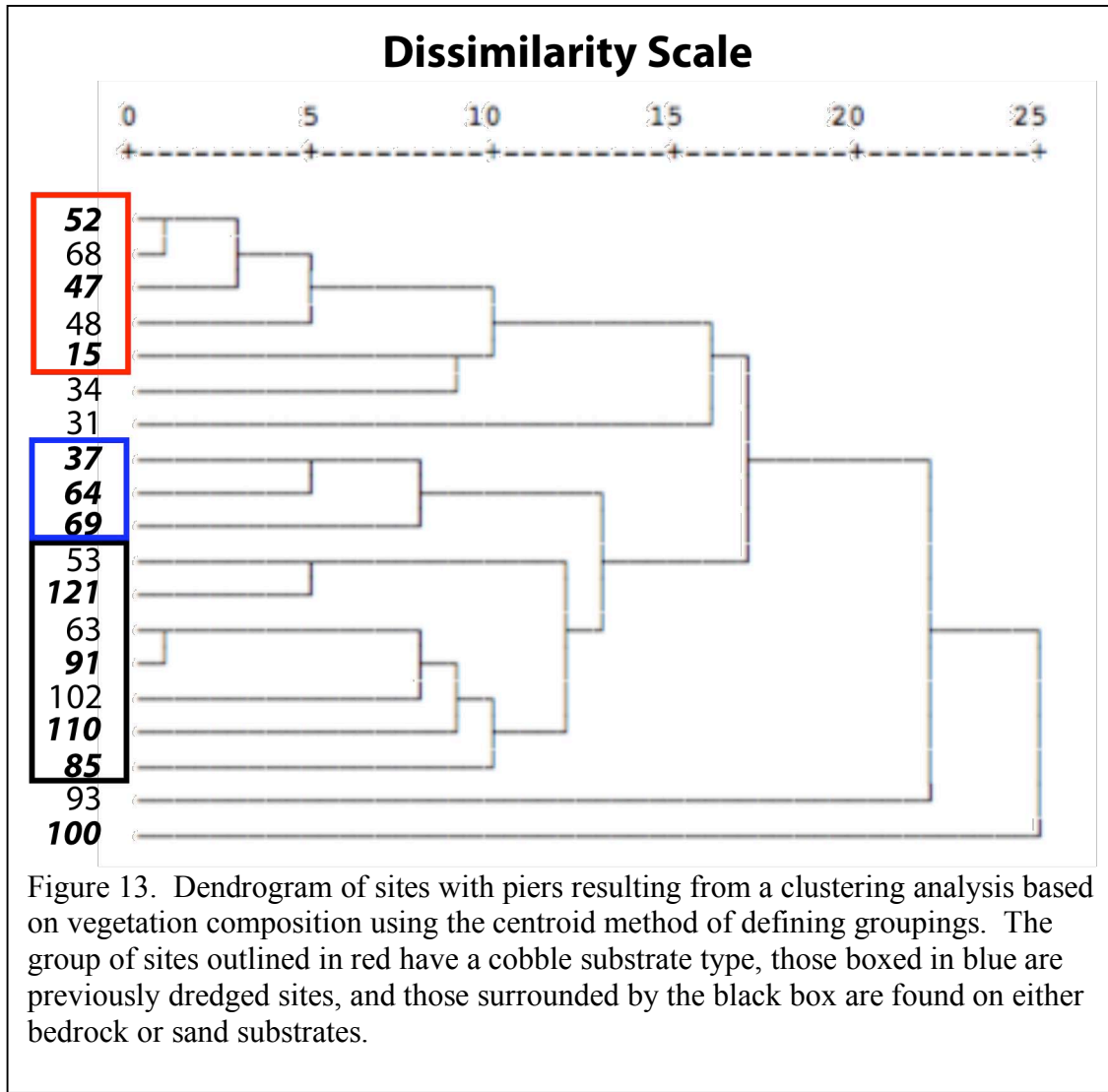


Table 12. Results from separate Kruskal-Wallis tests run for the effects of Dredge history on vegetation density in rake samples. Significant effects of dredging for each Exposure/Substrate combination are indicated with asterisks (*=significant, **=highly significant).

Exposure	Substrate Type	df	Chi-Square	P-value
Exposed	Bedrock	1	2.797	0.094
Exposed	Cobble	1	5.498	0.019 *
Exposed	Sand	1	9.395	0.002 **
Protected	Bedrock	1	6.129	0.013 *
Protected	Cobble	1	1.669	0.196
Protected	Sand	1	3.285	0.070

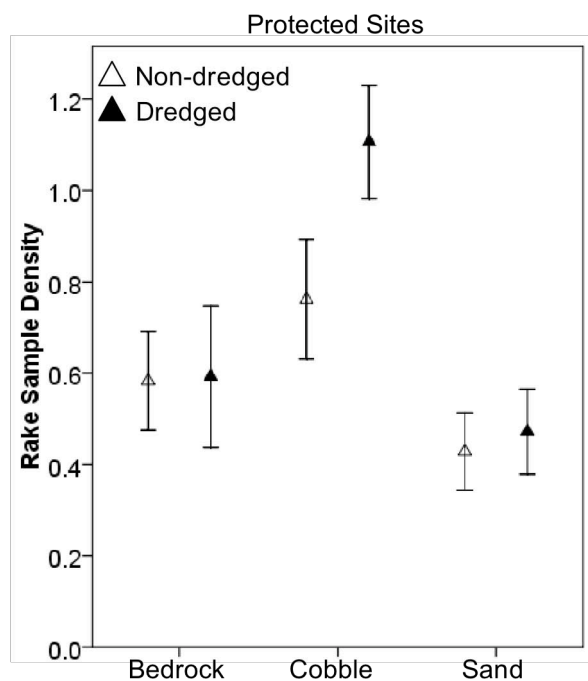
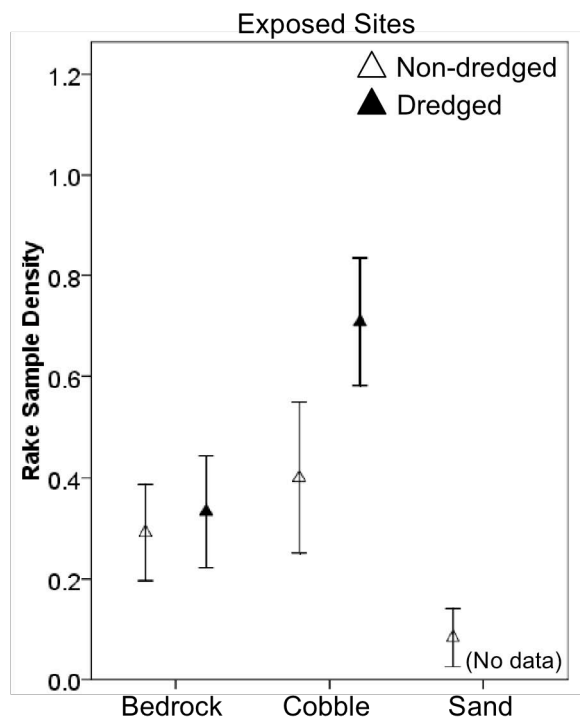


Figure 14. Density of vegetation (mean \pm 1 SEM) in rake samples from exposed (top) and protected (bottom) sites on three types of substrate (bedrock, cobble, sand) at locations without piers during summer 2008. Open symbols indicate non-dredged sites, filled symbols indicate sites previously dredged.

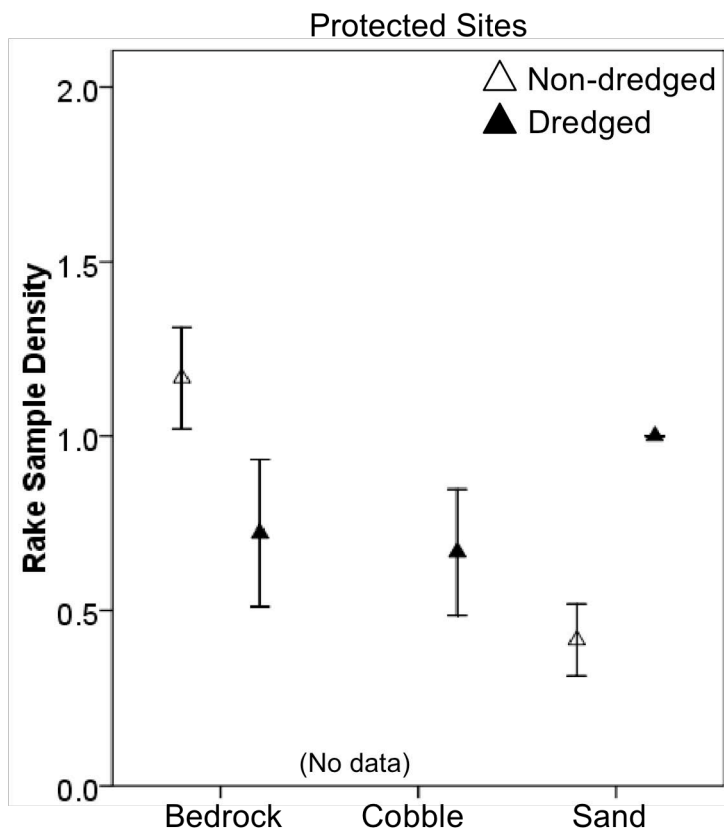


Figure 15. Density of vegetation (mean \pm 1 SEM) in rake samples from protected sites on three types of substrate (bedrock, cobble, sand) at locations with piers during summer 2008. Open symbols indicate non-dredged sites, filled symbols indicate previously dredged sites. No data were obtained for sites on cobble substrate that had not been dredged.

this combination. At locations with sand substrate with piers, vegetation density on rakes was significantly higher at previously dredged sites (Figure 15). There was no overall significant effect of position in the channel on rake density ($P > 0.05$ for all effects).

Benthic Macroinvertebrate Analysis:

The benthic invertebrates collected in grab samples were enumerated into 11 broad taxonomic categories (Table 13). There were from 0 to 8 groups identified in any one site. The most diverse sites in terms of number of taxa occurred at sites with cobble substrates. Of the top six sites ranked according to taxa richness, 5 were sites with cobble substrate. The most frequently occurring taxa were midge fly larvae, found in 79% of the sites, and amphipods observed in 49% of the locations sampled (Table 14). Dredging history did not significantly affect the number of taxa observed at a site except in the sandy substrate areas (Table 15). Dredged sites with sand substrate generally had higher numbers of taxa than nondredged sites (mean dredged = 3.40 taxa, nondredged = 2.63) based on sites without piers. The only aquatic invasive species recorded among the benthic invertebrates was the zebra mussel (*Dreissena polymorpha*). Live specimens were found only in about 9% of the sites examined. However, nearly half of the sites did contain evidence of dead zebra mussels (i.e. shells) in either the sediment, rake or video transect samples (19 out of 44 sites).

There was no significant effect of dredging on any of the individual macroinvertebrate abundances, but both substrate and exposure of locations did significantly affect abundance for amphipods, midge fly larvae and ostracods (Table 16). Although abundances were not significantly different overall at dredged and nondredged

Table 13a. Composition and abundance of benthic macroinvertebrates observed at sites along the Green Bay shoreline of Door County, WI during summer 2008. Values represent the average abundance index value estimated in grab samples. Aquatic invasive species are highlighted. Site numbers for dredged sites are in bold italics. See Table A1 and Figure A1 for site location details.

Taxa	11	12	16	17	21	23	24	30	31	33	34	37	44	45	47	48	52	53	63	64	65	68	69
Amphipods		3	1	2	1	1			3	3	3		2	2				1					2
Flatworms				2																			
Isopods			1									1		2									
Leech				1																			
Mayfly nymph					1	1			1			1	1		1								1
Midgefly Larvae	2		2	2	2	2		1	2	2	3	2	2	3	2	1	2	2			3		2
Water Mite		2	2	2	1	2					2		1										1
Nematodes				2	2	2			3	3	2		2										
Ostracods	2		1	2	3	3				2	2		2	1									1
Tubifex larvae				1					2	1		1	2	1	2	2							
Zebra Mussel	2		2			2		2															
TOTAL TAXA	3	2	6	8	6	7	0	2	5	5	5	4	7	5	3	2	1	2	0	0	1	0	5

Table 13b. Composition and abundance of benthic macroinvertebrates observed at sites along the Lake Michigan shoreline of Door County, WI during summer 2008. Values represent the average abundance index value estimated in grab samples. Aquatic invasive species are highlighted. Site numbers for dredged sites are in bold italics. See Table A1 and Figure A1 for site location details.

Taxa	71	72	80	81	83	84	85	90	91	92	93	100	101	102	110	111	112	113	120	121
Amphipods	1	1	2	2	1	2				3	1			2						
Flatworms																				
Isopods									1											1
Leech	1																			
Mayfly nymph		1			2															1
Midgefly Larvae	2	3	3	3	3	3	3	3	3	3	3	2	3	3			1			3
Water Mite			1	2						1										2
Nematodes		2	2	2	3			1												2
Ostracods			1	2	2			1	1		1									
Tubifex larvae		2																		2
Zebra Mussel																				
Total Taxa	3	5	5	5	5	2	1	3	3	3	3	1	1	2	0	0	1	0	0	6

Table 14. Percent of all sites where benthic invertebrate taxa were observed. Aquatic invasive species are highlighted.

Taxa	Occurrence (Percent)
Amphipods	48.8
Flatworms	2.3
Isopods	11.6
Leech	4.7
Mayfly nymph	23.3
Midgefly larvae	79.1
Water Mite	27.9
Nematodes	30.2
Ostracods	37.2
Tubifex larvae	23.3
Zebra Mussel	9.3

Table 15. Results from Kruskal-Wallis tests for the effects of Dredge history on macroinvertebrate taxa richness in grab samples from sites without piers. Significant effects of dredging for each Exposure/Substrate combination are indicated with asterisks (*=significant, **=highly significant).

Exposure	Substrate Type	df	Chi-Square	P-value
Exposed	Bedrock	1	0.333	0.564
Exposed	Cobble	1	0.288	0.592
Exposed	Sand	1	9.395	0.002 **
Protected	Bedrock	1	1.607	0.205
Protected	Cobble	1	0.046	0.830
Protected	Sand	1	8.667	0.003 **

Table 16. Analysis of variance (ANOVA) results for the full dataset on A) Amphipod, B) Midgefly, and C) Ostracod abundance. A Type III ANOVA model was employed for these analyses. Significant effects of source factors are indicated with asterisks (*=significant, **=highly significant).

A) Amphipod Abundance

Source	df	Significance Level
Dredge	1	0.070
Substrate Type	2	0.125
Exposure	1	0.001 **
Dredge X Substrate	2	0.239
Dredge X Exposure	1	0.853
Substrate X Exposure	2	0.002 **
Dredge X Substrate X Exposure	2	0.002 **

B) Midgefly Abundance

Source	df	Significance Level
Dredge	1	0.652
Substrate Type	2	<0.001 **
Exposure	1	<0.001 **
Dredge X Substrate	2	0.096
Dredge X Exposure	1	0.245
Substrate X Exposure	2	<0.001 **
Dredge X Substrate X Exposure	2	0.058

C) Ostracod Abundance

Source	df	Significance Level
Dredge	1	0.491
Substrate Type	2	0.041 *
Exposure	1	0.030 *
Dredge X Substrate	2	0.547
Dredge X Exposure	1	0.941
Substrate X Exposure	2	0.489
Dredge X Substrate X Exposure	2	0.945

sites, this is not unexpected because abundances were measured on a geometric scale giving rise to large variances. Considering the geometric nature of the abundance scale, it is important to note the trends for some groups. For instance, amphipods were generally less abundant at previously dredged sites, by a 5- or 10-fold difference depending on location (Figure 16). Similar patterns were observed for midge fly larvae and for ostracods as well (Figures 17 & 18). In addition, exposed sites typically had lower abundances of macroinvertebrates than protected locations, and sites with piers had lower abundances than those without piers.

Consistent with the abundance patterns noted above, the cluster analysis based on community composition of the macroinvertebrate taxa identified groupings that differed based on substrates and exposure locations, but also defined some groups based on dredging history. There were two clear groupings in the nonpier data set. One grouping included sites that had either bedrock or sand substrates (Figure 19). These sites were essentially devoid of benthic invertebrates (Table 17). The other grouping included sites that had not previously been dredged and contained various taxa such as amphipods, nematodes, ostracods and midgefly larvae. For the sites with piers, one grouping was defined by sites in exposed areas, all of which did not have benthic invertebrates in grab samples (Figure 20). A second grouping was for sites that were previously dredged, and contained exclusively midgefly larvae and amphipods.

Particle grain size and shape were correlated with some aspects of the macroinvertebrate data. There was a significant overall positive correlation between particle grain size and amphipod abundance (Pearson Correlation Coefficient, $r = 0.245$, $n=72$, $P=0.011$). Both particle size and particle shape were negatively correlated with the

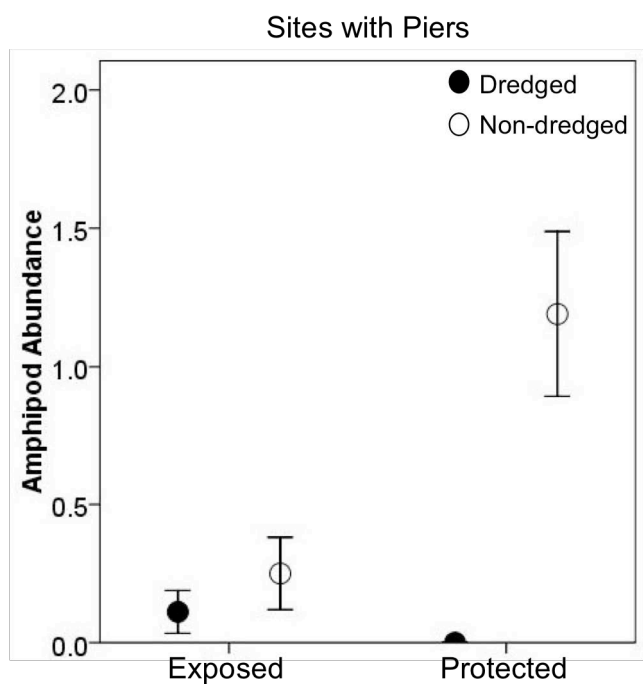
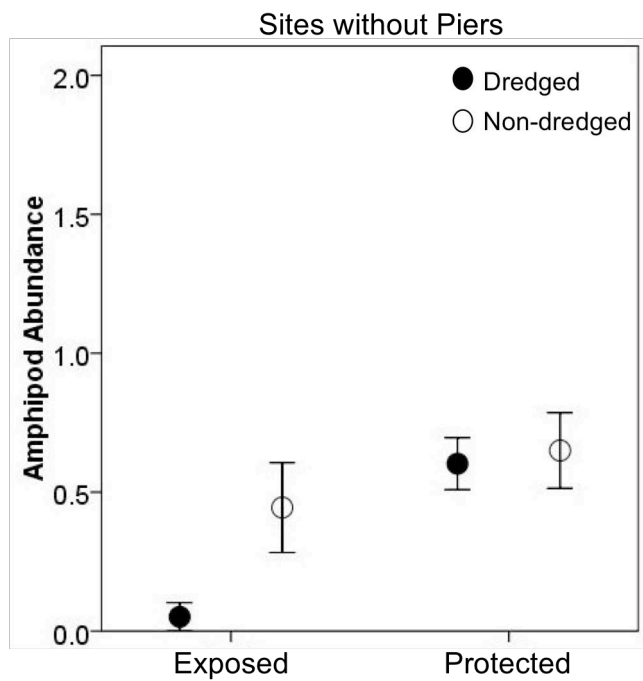


Figure 16. Amphipod abundance (mean \pm 1 SEM) in grab samples from exposed or protected sites at locations without (top) or with (bottom) piers during summer 2008. Open symbols indicate non-dredged sites, filled symbols indicate previously dredged sites.

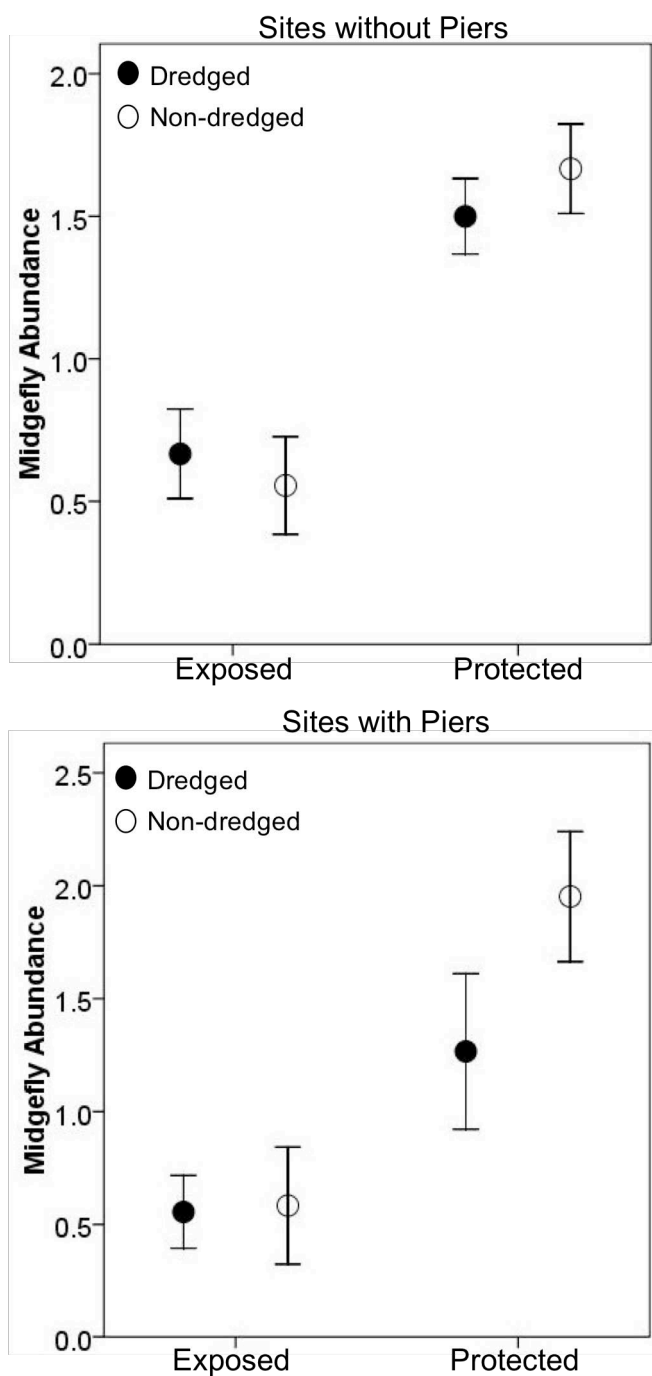


Figure 17. Midgefly abundance (mean \pm 1 SEM) in grab samples from exposed or protected sites at locations without (top) or with (bottom) piers during summer 2008. Open symbols indicate non-dredged sites, filled symbols indicate previously dredged sites.

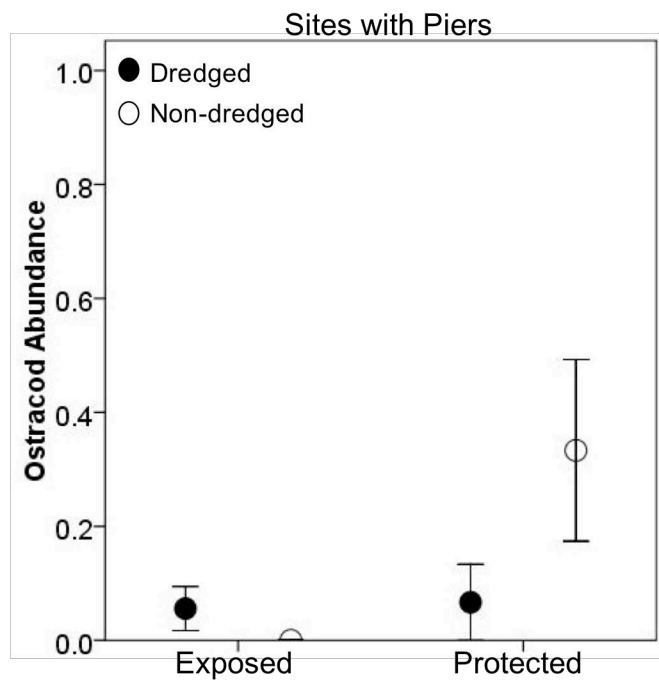
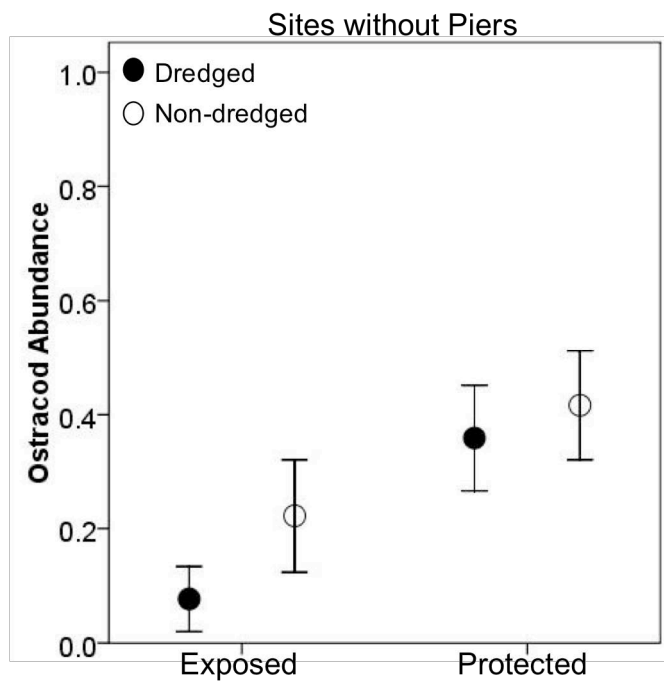


Figure 18. Ostracod abundance (mean \pm 1 SEM) in grab samples from exposed or protected sites at locations without (top) or with (bottom) piers during summer 2008. Open symbols indicate non-dredged sites, filled symbols indicate previously dredged sites.

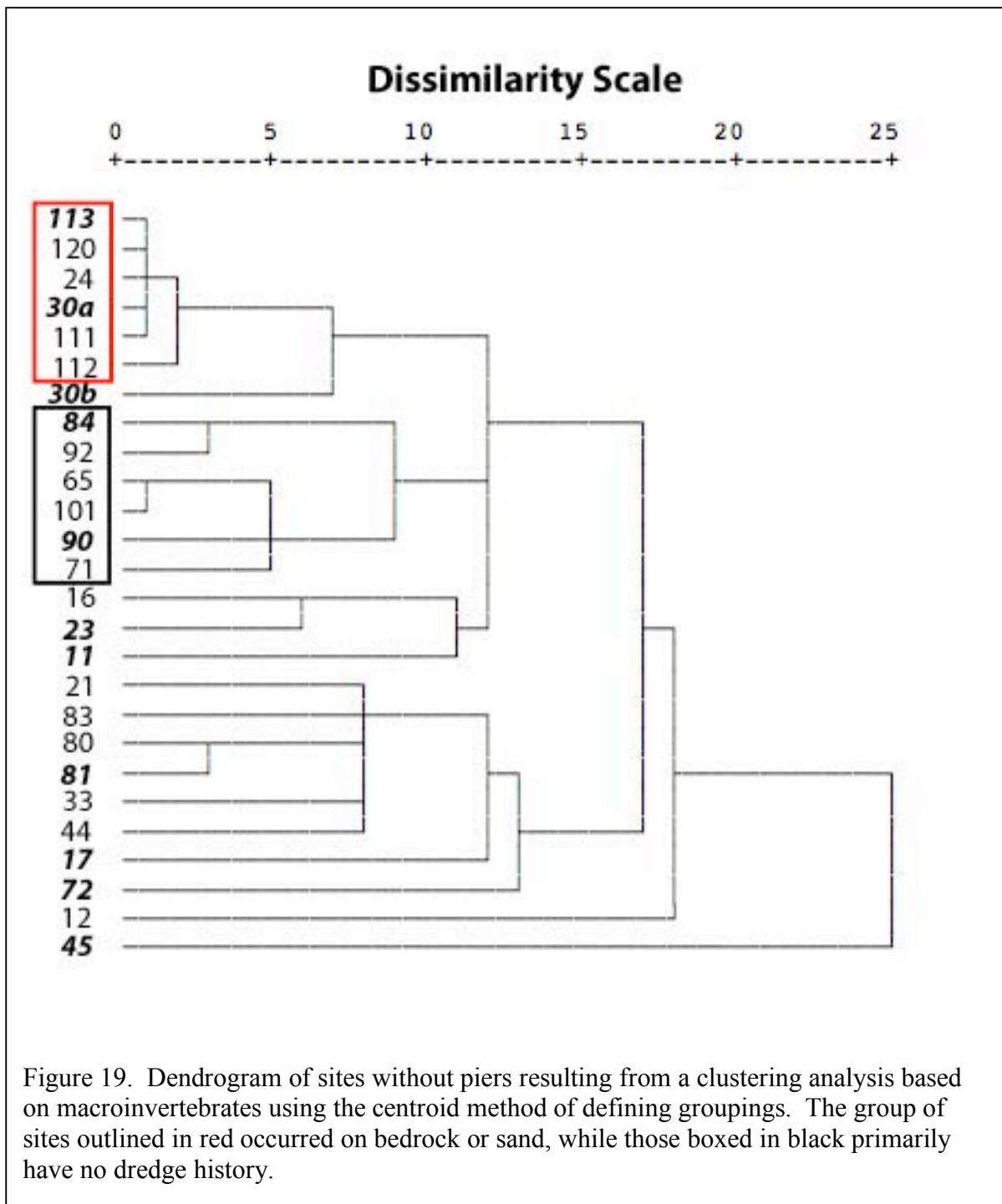


Figure 19. Dendrogram of sites without piers resulting from a clustering analysis based on macroinvertebrates using the centroid method of defining groupings. The group of sites outlined in red occurred on bedrock or sand, while those boxed in black primarily have no dredge history.

Table 17. Benthic macroinvertebrate associations observed at sites in groupings defined by cluster analysis using a centroid agglomerative method.

Site without Piers

Bedrock/Sand Grouping

No benthos

Nondredged Grouping

Midgefly Larvae

Amphipods

Nematodes

Ostracods

Sites with Pier

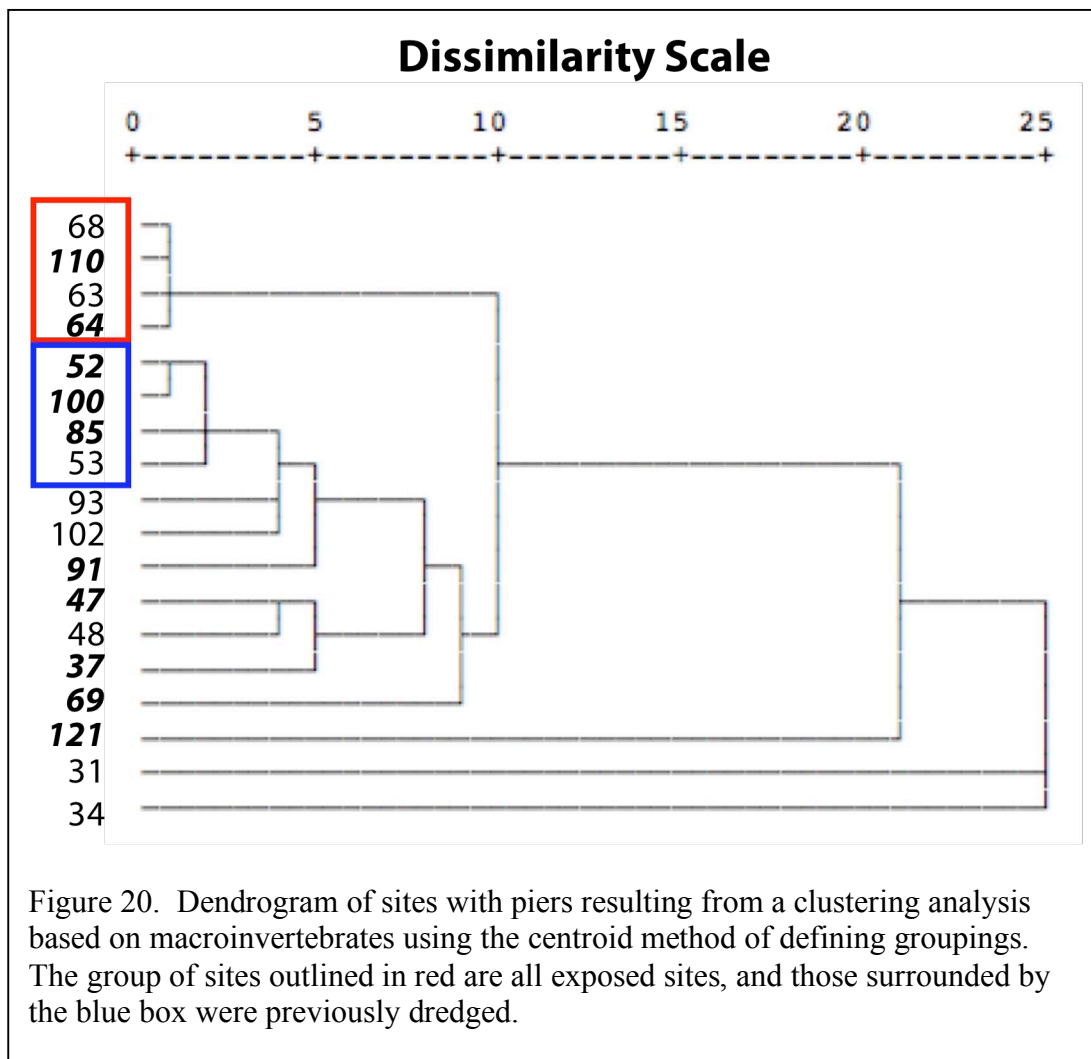
Exposed Grouping

No benthos

Dredged Grouping

Midgefly Larvae

Amphipods



total number of macroinvertebrate taxa (size: $r = -0.20$, $n = 287$, $P = 0.001$; shape: $r = -0.194$, $n = 152$, $P = 0.017$). These data indicate that more amphipods and midge fly larvae are normally found in sites with larger grain sizes, but that fewer taxa overall will be found in these sites. In addition, fewer taxa are found in sites with rounder sediments particles.

Conclusions and Summary

Dredging Effects:

There were clear and obvious differences between sites that had been previously dredged and those without any dredging history. Previously dredged sites exhibited the following characteristics compared to non-dredged sites:

- significantly smaller sediment grain size and rounder particles
- significantly greater amounts of silt and occasional low oxygen conditions (up to 70 cm of silt was observed in the middle of dredged channels)
- higher amounts of vegetation and more extensive coverage of sediment by vegetation (with greater coverage in the middle of the channel)
- significantly greater number of plant species (more than twice as many species on average)
- distinct vegetation composition, including two invasive plant species (Eurasian water-milfoil and Curly-leaf pondweed) and Muskgrass
- at bedrock sites, significantly more benthic algae such as *Cladophora* in areas adjacent to dredged channels compared to mid-channel or non-dredged sites
- trend towards lower macroinvertebrate abundance but higher diversity

These differences demonstrate that there have been long-term and cumulative impacts of dredging on both physical and biological characteristics of near shore environments around Door County, WI. These differences are distinct from the expected effects of the varying exposure and substrate conditions that occur along the shoreline.

The significantly greater abundance of smaller particles observed at previously dredged sites supports the conclusion that dredged channels accumulate smaller particles. Based on the settling characteristics of particles in moving water, this is likely due to reduced flow in channels and subsequent retention of smaller particles (Wood & Armitage 1979). In addition, the observed higher abundance of rounder particles in previously dredged locations is also consistent with previous expectations. Rounder particles generally sink faster because of reduced resistance (McAnally 2000, Germano and Cary 2005). Rounder particles also usually indicate longer exposure to eroding forces, likely during transport. In addition, sorting processes that typically occur during settling based on flow velocity differences also help explain the higher prevalence of smaller, rounder particles at dredged locations (Environment Canada 2002, Germano and Cary 2005). Round particles often result in more highly compacted sediments, decreased oxygen permeability as well as reduced interstitial spaces. This could be one possible explanation of the strong smell of sulfur observed in some of the dredged channels where large amounts of black silt had accumulated.

Higher abundance of smaller particles was also related to increased macrophyte density at previously dredged sites, especially on cobble and sand substrates. Previous work has shown that macrophytes reduce water speed and overall water movement, as well as trap sediment among their leaves and stems (Fonesca & Fisher 1986). In

addition, fine sediment is often generated by the decomposition of macrophytes (Wood & Armitage 1997).

Based on these data the following explanation of the effects of dredging, especially in locations with cobble and sand substrates, seems reasonable. Construction of a dredged channel produces a new depression in the near shore environment that has numerous consequences: 1) the channel becomes an environment with reduced water flow, 2) this lower flow environment results in increased deposition of smaller, rounder particles, 3) macrophytes can establish themselves in these lower flow environments, 4) the presence of macrophytes further reduces water flow, leading to further deposition and accumulation of sediment.

A further effect of dredging was an increased diversity and density of macrophytes. It is well documented that both physical disturbance and invasions by exotic species often result in increased diversity in aquatic ecosystems (Pickett & White 1985, Ward & Ricciardi 2007). The clustering analysis identified previously dredged sites as having a distinct vegetation composition. This association included both of the invasive macrophyte species documented in this study (Eurasian water-milfoil, and Curly-leaf pondweed). Although we did not measure densities of individual macrophyte species, others have shown that stands of invasive macrophytes are denser than native species (Kelly & Hawes 2005), especially Eurasian water-milfoil (e.g. Budd et al. 1995). In addition, another long-term effect of channel dredging can be increased nutrient availability for macrophytes following disturbance of the sediment (Davis & Brinson 1980).

Macroinvertebrate abundance tended to be lower in previously dredged sites, but the high amount of variability among exposure conditions and substrate types resulted in non-significant dredge effects overall. The trends towards lower abundances, especially for amphipods and midge fly larvae, are even more interesting because expectations from other studies would suggest that just the opposite should have been observed based on macrophyte densities. Overall, macrophyte density is typically positively correlated with macroinvertebrate abundance, often due to increased oxygenation of the sediments by roots and increases in food sources derived from decaying plant material (Sagova et al. 1983, Sagova-Mareckova 2002, Strayer et al. 2003). Invasive plant communities often harbor higher diversity and density of macroinvertebrates as well (Kelly & Hawes 2005), which may help explain the significantly higher taxon diversity at locations with sand substrate. Macrophyte species with finely dissected leaves, like the invasive Eurasian water-milfoil, are especially known to harbor increased densities of macroinvertebrates like midge fly larvae (Gerrish & Bristow 1979). However, exposure and substrate conditions have been shown to be two key factors determining community structure in macroinvertebrates, and this appeared to be the case in this study as well.

Exposure Effects:

Sites exposed to waves and currents from either Green Bay or Lake Michigan generally shared some common characteristics based on the results of this study.

Exposed sites exhibited the following traits compared to protected sites:

- larger particle sizes and a more rounded particle shape
- lower vegetation density based on both rake density and area coverage

- higher abundance of benthic algae, especially adjacent to previously dredged channels
- lower macroinvertebrate density and diversity

Stress from wave action is the most likely reason for the effects of exposure conditions on the characteristics studied. Higher speed and more frequent water movement are known to sort sediments and prevent accumulation of smaller particles (Wood & Armitage 1997, McAnally 2000). Exposure to waves and currents can also prevent establishment and growth of macrophytes. Even once established, fragmentation of leaves and stems by wave action can be a significant factor limiting the growth of macrophytes in exposed sites (Davis & Brinson 1980). Exposure is also a major factor determining macroinvertebrate composition, with fewer taxa able to survive the mechanical stresses in areas with higher wave energy (Barton & Hynes 1978, Metzler & Sager 1986, Tolonen et al. 2001). Plus, the lack of macrophytes can further contribute to lower density and diversity of macroinvertebrates by failing to provide refuges from predatory fishes (Tolonen et al. 2001). Overall, the stress encountered in exposed coastal shorelines appears to preclude the development of extensive macrophyte and macroinvertebrate communities. As a result, the negative effects of dredging on these aspects of biological communities will likely be less severe in exposed sites than in protected locations.

Substrate Effects:

In addition to the clear overall effects of dredging and exposure, there were also obvious differences among sites with different types of substrate.

- macrophytes were more abundant on cobble and sand than on bedrock sites

- benthic algae was more abundant on bedrock than cobble or sand
- sites with cobble substrate contained the highest diversity of macroinvertebrates
- amphipod abundance was positively related to sediment particle size

Locations with primarily a bedrock substrate are relatively harsh environments for organisms. The lower macrophyte abundance at bedrock sites is consistent with previous work showing that these environments are less suitable for root growth and attachment and can have lower nutrient availability for plant growth (Davis & Brinson 1980).

However, benthic algae such as *Cladophora* and *Chara* can thrive in these environments because they require solid surfaces for attachment and derive their nutrients directly from the water (Dodds & Gudder 1992). This could also explain why benthic algae were more abundant outside of the dredged channels because the smaller, loose particles in the middle of channels would provide a less suitable substrate for the algae. Consequently, dredging impacts will be related more to benthic algae abundance and coverage in areas with primarily bedrock substrates and less with macrophyte effects.

Cobble and sand provide a better substrate for macrophyte growth because they can provide more stability for root establishment and higher nutrient availability than areas with primarily a bedrock substrate (Davis & Brinson 1980). Between cobble and sand substrates, cobble areas exhibited higher growth of macrophytes overall, likely due to both higher stability for root and rhizome production and higher nutrient retention and availability. Cobble substrates have a wider particle size range and contain more organic matter than sand substrates generally (Davis & Brinson 1980, Wood & Armitage 1997). While sand may be a poorer environment for macrophyte growth, we did observe significant increases in macrophytes in previously dredged locations with primarily a

sand substrate. Macrophytes were significantly higher in abundance and area coverage in the middle of dredged channels. This is likely due to the accumulation of smaller particles of a more organic nature (i.e. silt) in channels, providing increased nutrients for plant growth compared to adjacent sandy areas. A problem with extensive macrophyte growth in areas with cobble and sand substrates is thus an important long-term and cumulative impact of dredging.

Sites with cobble substrate exhibited the highest diversity and abundance of macroinvertebrates. It is well documented that increased heterogeneity of physical space provides more refuges from predation for macroinvertebrates (Barton & Hynes 1978, Tolonen et al. 2001), and the cobble substrates provide this kind of habitat. This is further supported by the significant positive correlations between amphipod abundance and particle size in this study. This is consistent with results in other studies showing positive correlations of amphipods and sediment grain size (Barton & Hynes 1978, Sagova et al. 1983, Sagova-Mareckova 2002). Because cobble areas had higher abundances overall of macroinvertebrates, it is also not surprising that the negative effects of dredging on macroinvertebrates were more obvious in these locations.

Pier Effects:

Testing the for effects of piers was not part of the original design of this study, but we were able to sample an additional set of sites with piers that fulfilled most of the desired aspects of our study at least once during the summer. Based on this limited set of data, it was observed that sites with piers showed a tendency to have higher abundances of macroinvertebrates, especially at protected sites. In addition, there was a trend of greater impact of dredging on abundance of amphipods, midge fly larvae and ostracods.

Aside from these differences, there was no clear effect of piers that was separate from the dredging, exposure or substrate type effects. However, a more extensive study focused on this topic would be required to make any definitive conclusions about this topic.

Finally, some features of sites were not significantly affected by previous dredging. There was no significant difference in occurrence of invasive plants or zebra mussels at previously dredged versus non-dredged sites. This was mainly due to the wide distribution of these species. The invasive plant species documented, Eurasian water-milfoil Curly-leaf pondweed, were occurred commonly in the waters around Door County (documented in over 50% and more than 25% of the sites, respectively). Live specimens of zebra mussels were found in only 9% of the shallow near shore zones examined, but shells of dreissenid mussels were found in over 50% of the sites, as expected based on the common prevalence of mussels in these locations following the successful invasion of Green Bay and Lake Michigan almost two decades ago.

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